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AN APPROACH FOR
ASSESSING MISSILE SYSTEM
DORMANT RELIABILITY

January 30, 1981

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FOREWORD

This final technical report, BDM/A-81-016-TR is submitted to the Air Force Test and Evaluation Center by The BDM Corporation, 1801 Randolph Rd. SE, Albuquerque, NM. 87106, in accordance with the requirements of Paragraph 6.6.2 of Subtask Statement 1.11/3, Contract F29601-79-C-0051. The Air Force Technical Project Officer for this task was Mr. Neal F. Chamblee, AFTEC/LG4. Principal contributors to this report were Richard D. Trapp, and William D. Farmer. Other contributors were Robert R. Graber and Dr. Ronald A. Luhks. Dr. Luhks was also the BDM Program Director.

This study effort relied upon "Dormant Reliability Effects Analysis and Recommended Methodology", BDM/TAC-80-629-TR, and the research efforts of William B. Lindquist, Mary Jane Pence, Raymond J. Walkowski, Jerry C. Eatherly and Dr. Ronald A. Luhks documented in that technical report as a baseline and point of departure.

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TABLE OF CONTENTS

<u>Section</u>	<u>Page</u>
I INTRODUCTION	1
1.1 PURPOSE	1
1.2 SCOPE	1
1.3 BACKGROUND	1
1.4 STUDY APPROACH	2
II THE NEED FOR CONSIDERING DORMANCY EFFECTS	7
2.1 TRENDS IN MISSILE SYSTEMS	7
2.2 DORMANCY AND MISSILE SYSTEMS	7
2.3 WEAPON SYSTEM DEVELOPMENT PROCESS	8
2.4 TEST AND EVALUATION	9
2.5 POLICY, GUIDANCE, AND DIRECTION	9
2.6 IS THERE A NEED?	10
III CHARACTERIZATION OF THE DORMANCY PROBLEM	11
3.1 GENERAL NATURE OF THE PROBLEM	11
3.2 DEFINITIONS	12
3.2.1 All Up Round (AUR)	13
3.2.2 Wooden Round	13
3.2.3 On-Equipment Maintenance	14
3.2.4 Off-Equipment Maintenance	14
3.2.5 Life Cycle	15
3.2.6 Life Cycle Profile	15
3.2.7 Service Life	15
3.2.8 Shelf Life	15
3.2.9 Operating	16
3.2.10 Non-Operating	16
3.2.11 Storage	17
3.2.12 Inherent Dormat Reliability	17
3.2.13 Operationally Ready Storage	17
3.2.14 Dormancy	18
3.2.15 Alternate Definitions of Dormancy	20
3.3 DORMANT RELIABILITY	22
3.4 DORMANCY EFFECTS	22
3.5 INHERENT LIMITATIONS	24
3.6 LIMITATIONS ASSOCIATED WITH CURRENT APPROACHES	25
3.7 ITERATIVE AND LONG TERM NATURE OF THE PROCESS	25

THE BDM CORPORATION

TABLE OF CONTENTS (Continued)

<u>Section</u>		<u>Page</u>
IV	EXPERIENCE AND THE "STATE OF THE ART"	27
4.1	CURRENT METHODOLOGIES	27
4.1.1	Parts Count and Stress Analysis Prediction	27
4.1.2	Failure Rate Modification Factors	28
4.1.3	Testing	30
4.2	EXAMPLES OF SPECIFIC EXPERIENCE	33
4.2.1	TOW, MGM-71	33
4.2.2	MAVERICK, AGM-65	34
4.2.3	COPPERHEAD, M-712	34
4.2.4	ALCM, AGM-86	35
4.2.5	I-HAWK, MIM-23B	37
4.3	SUMMARY	39
V	NECESSARY CONSIDERATIONS AND PREREQUISITES	41
5.1	ACQUISITION PROCESS CONSIDERATIONS	41
5.2	SYSTEM SPECIFIC CONSIDERATIONS	43
5.2.1	Hardware	44
5.2.2	Environment	44
5.2.3	Concept of Operation	44
5.2.4	Maintenance Concept	45
5.2.5	Life Cycle Profile	45
5.3	TEST AND EVALUATION CONSIDERATIONS	50
5.3.1	Test Limitations	51
5.3.2	Sampling	51
5.3.3	Projection Methodologies	52
5.3.4	Validation and Verification	53
VI	TOOLS AND TECHNIQUES FOR POTENTIAL AFTEC APPLICATION	55
6.1	AVAILABILITY AND APPLICABILITY	55
6.2	INITIAL ESTIMATES	55

THE BDM CORPORATION

TABLE OF CONTENTS (Continued)

<u>Section</u>		<u>Page</u>
	6.2.1 MIL-HDBK-217C	55
	6.2.2 Piece Parts for Non-Electronics	56
	6.2.3 Piece Part Surrogates	56
	6.2.4 Piece Part Computer Codes	57
	6.2.5 Comparability Analysis	57
	6.2.6 K Factors	58
	6.2.7 Other Estimating Techniques	63
	6.2.8 Initial Estimating Techniques - Overview	67
	6.3 PROJECTIONS TO MATURITY	71
	6.4 TESTING FOR DORMANT RELIABILITY	71
	6.4.1 Testing Considerations by Missile Subsystem	72
	6.4.2 OT&E Testing Perspective	76
	6.4.3 Test Sensitive Elements	77
	6.5 EVALUATING DORMANCY EFFECTS	83
	6.6 EVALUATING THE WOODEN ROUND	83
VII	DATA SOURCES	87
	7.1 OVERVIEW	87
	7.2 AIR FORCE DATA	87
	7.3 ARMY DATA	88
	7.4 NAVY DATA	89
	7.5 DATA SYSTEMS LIMITATIONS	90
VIII	DORMANT RELIABILITY ASSESSMENT APPROACH	91
	8.1 OVERVIEW	91
	8.2 IMPLEMENTATION GUIDELINES	91
	8.2.1 Planning	93
	8.2.2 IOT&E	94
	8.2.3 FOT&E	95
IX	CONCLUSIONS AND RECOMMENDATIONS	97
	9.1 CONCLUSIONS	97
	9.2 RECOMMENDATIONS	98
ANNEX A		A-1
ANNEX B		B-1
ANNEX C		C-1
ANNEX D		D-1
ANNEX E		E-1
ANNEX F		F-1

THE EDM CORPORATION

LIST OF ILLUSTRATIONS

<u>Figure</u>		<u>Page</u>
1	Study Approach Methodology	3
2	Dormancy: Subsystem Level, Based on Subsystem Installed in AUR, Nonoperating Time, on Equipment Maintenance, and Functional Checks/Bit in Storage (Includes Operationally Ready Storage as a Subset)	19
3	Alternate Definition 1: System, Subsystem and Component Level, Based on Storage Area <u>F</u> 10% Energized	21
4	Alternate Definition 2: System Level, Based on AUR with Less Than Normal or Periodic Stress	23
5	Reliability Life Cycle Activities	42
6	Typical Missile System Life Cycle Profiles	46
7	Comparison of the Various Sidewinder Types with the AIM-9 B Sidewinder IA (taken from <u>International Defense Review</u> , Special Series 10, 1980, without modification)	59
8	Environmental Severity Ratios and Influence Matrix	62
9	Hypothetical Inherent Dormant Reliability Predicted by Regression Analysis	65
10	Overview of Dormant Reliability Related Tests	73
11	OT&E Test Sensitive Decision Process	78
12	Summary of OT&E Test Sensitive Elements (Tactical Air-to-Air Missile)	79
13	Example Missile Reliability after 5 Years of Dormant Deployment Under "Wooden Round" and Periodic Test Concept (Does Not Include Type 2 and 6 Failures)	85
14	Dormant Reliability Assessment Approach	92
C-1	Life Cycle Model For Dormant Missile with Periodic Test	C-3

THE BDM CORPORATION

LIST OF ILLUSTRATIONS (Concluded)

<u>Figure</u>		<u>Page</u>
C-2	Reliability Degradation with No Test Deployment Concept	C-7
C-3	Missile Reliability after 5 Years of Dormant Deployment Under "Wooden Round" and Periodic Test Concept	C-11

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SECTION I INTRODUCTION

1.1 PURPOSE.

This study was conducted to investigate the effects of dormancy on missile systems/subsystems, identify current dormant reliability prediction methodologies, and provide an approach for assessing dormant reliability and the effects of dormancy on missile systems. This report documents the results of the study effort and recommends an approach which is applicable throughout the life cycle of the missile system.

1.2 SCOPE.

This report is intended to summarize the current state-of-the-art in identifying the effects of dormancy as it relates to operational reliability. It is not intended to provide an exhaustive treatment of dormant reliability. Documentation provided by AFTEC and additional material and information acquired by The BDM Corporation during the study were used to formulate an approach for dealing with missile system dormancy as part of the OT&E process. It is clear that additional data probably exist; it is not as apparent that additional research could provide greater insight than that necessary to accomplish this task. The approach presented in this report will provide a framework in which to develop the detailed test methodology necessary to evaluate the effects of dormancy on a specific missile system.

1.3 BACKGROUND.

The reliability of military systems after long periods of dormancy has been a major concern throughout military history. A system taken out of storage is expected to accomplish its mission without a performance degrading malfunction. In early military history, spoilage of items such

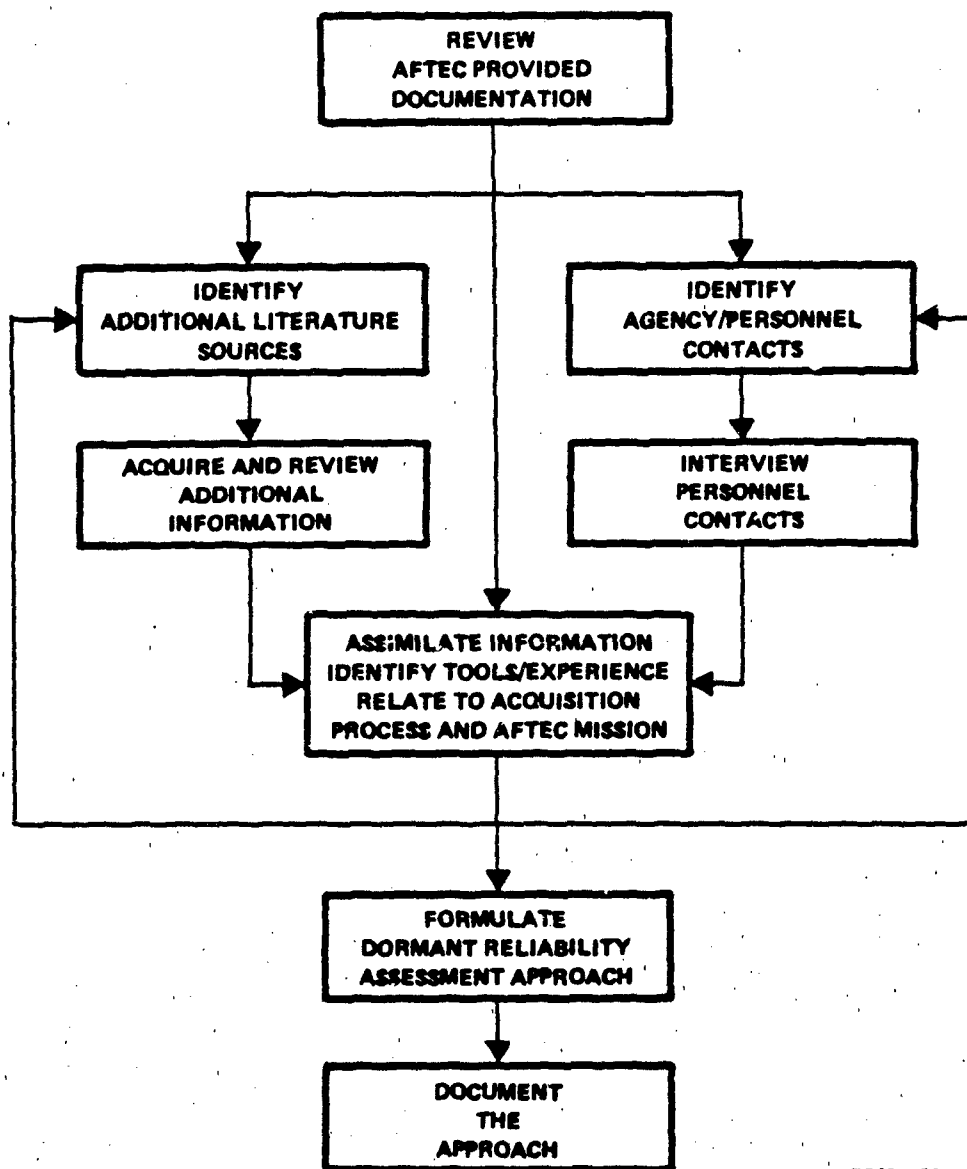
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as food and gunpower was a major concern. A few years ago, when aircraft availability exceeded flying requirements, care was taken to periodically move parked aircraft to mitigate the effects of nonuse (e.g., flat tires, fluid drain, etc.). As military systems have continued to become more sophisticated, complex, and expensive, and as their expected response time has become shorter, the need for higher reliability has increased. Inherent in that need is a requirement for higher dormant reliability.

AFTEC is currently involved in the OT&E of missile systems, and there is concern about the effects of dormancy because these systems spend a majority of their time in a non-operating environment. Some types of munitions (e.g., bombs, rockets, ammunition, etc.) typically spend extensive periods of time in storage and generally exhibit relatively high reliability. On newer missile systems, however, complexity is increasing, longer service lives are required, and periodic maintenance and checkouts are being reduced or eliminated. The Air Force is exploring the potential utility of the "wooden round" maintenance concept. Therefore, concern about the effects of dormancy on a missile system's operational reliability is growing, and development of an approach for assessing dormant reliability as part of the test and evaluation process is becoming increasingly important.

1.4 STUDY APPROACH.

The approach taken in this study effort is graphically portrayed in figure 1. The principal segments involved an extensive literature search; interviews with various interested individuals; identification of current techniques, methodologies, and experience; assessment of the applicability and useability of current procedures within the framework of OT&E; devising modifications to existing techniques or suggesting new ones where the current techniques are lacking or inadequate; and formulation and documentation of a structured approach for assessing the effects of dormancy on missile systems.



BDM-A-01-016-TR

Figure 1. Study Approach Methodology

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1.5 REPORT STRUCTURE.

This report has been structured to provide discussion of relevant topics in a logical progression which builds to the proposed approach. Section II presents a compilation of pertinent concerns about dormancy and establishes the need for considering its effects. The nature of the dormancy problem is characterized in section III with considerable effort devoted to the definitions of key words, terms, and expressions. Part of the dormancy problem is the current lack of a consistent lexicon. Section IV summarizes documented experience and techniques for estimating dormant reliability. Significant facets of the weapon system acquisition process, the specific missile system being developed, and the overall test and evaluation process which warrant special consideration in a dormant reliability evaluation are summarized in section V. In particular, the notion of the missile system's life cycle profile--the central theme of the recommended approach--and the essential need to formulate it early in the planning phase is introduced. The heart of the study effort is embodied in section VI. Specific analytical techniques and innovative test methods are described in terms of the applicability within various phases of the missile system acquisition and development process. Several data systems exist within the Services, but their useability is limited because of inherent inconsistencies in their structure and content--those limitations are discussed in section VII. Section VIII presents the bottom line--a structured approach for assessing dormant reliability within the context of a comprehensive test and evaluation program. Primary conclusions and recommended subject areas for further study are provided in section IX.

Several topic areas addressed in this report warrant more detailed discussion than is considered appropriate for the body of the report. Therefore, annexes to the report have been provided to address specific topics in greater detail. Annex A provides a discussion of MIL-HDBK-217B failure rate calculation procedures. Annex B describes some of the more prevalent causes of missile system dormant reliability degradation. The

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missile system's life cycle profile is the central theme in the approach to assessing dormant reliability, and an example of the life cycle modeling methodology is presented in annex C to demonstrate its utility. Annex D provides a discussion of the fundamental tool in life testing--the exponential distribution--and some methods for determining sample size requirements. Various electronic equipment screening methods employed during the infant mortality period are compared in annex E. Various reports, papers, text books, and other sources of information have been itemized in annex F.

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SECTION II THE NEED FOR CONSIDERING DORMANCY EFFECTS

2.1 TRENDS IN MISSILE SYSTEMS.

Missile systems which are or will be entering the Air Force weapons inventory during the 1980s can generally be described as more complex. The new generation missiles employ more sophisticated technologies in guidance and control, propulsion, and other major subsystems. Increased complexity and sophistication and their attendant higher development and production costs contribute substantially to longer service life requirements and perhaps smaller production quantities. Additionally, newer missile systems are being developed, as much as possible, to be deployed as "wooden rounds." Under this concept, missiles are accepted and deployed to operational units as "all up rounds" with minimal field-level checkout and maintenance.

2.2 DORMANCY AND MISSILE SYSTEMS.

Dormancy and its effect on weapon system reliability has been a concern throughout military history. Systems removed from storage are expected to perform without mission degrading malfunctions. The sophistication and complexity of modern weapons coupled with the rapid response time required to effectively counter the expected threat preclude extensive checkout and repair prior to employment. Dormancy in missile systems is a particular concern because these systems spend the majority of their life in a non-operating (e.g., storage, alert, captive carry, etc.) environment. The wooden round maintenance concept for missile systems clearly increases the ratio of non-operating time to operating time. In a typical missile system, even with periodic checkout, non-operating time could be as much as two million times longer than operating time. Even though the operating failure rate may be substantially greater than the non-operating failure rate, the significant difference in time between

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these two states makes dormancy a major factor to consider when attempting to estimate or project a mature missile system's operational reliability.

2.3 WEAPON SYSTEM DEVELOPMENT PROCESS.

Weapon system development is intended to provide capabilities to satisfy operational mission needs identified by using commands. At the first in a series of key decision points, Milestone 0, exploration of alternative solutions begins. During this phase of the program, the using command begins developing preliminary system operational concepts for the various alternatives. This general concept describes the intended purpose, employment, deployment, and maintenance concept for the weapon system. The relative importance or impact of dormancy on a missile system's reliability can be initially evaluated during this conceptual phase of the development process. As the development program progresses into its demonstration and validation phase, alternative solutions are refined and selected, operational and maintenance concepts are updated and finalized, and DT&E and IOT&E may be conducted. During full-scale engineering development, the missile system will be designed, fabricated, tested, and evaluated. IOT&E must be accomplished with the most realistic test events possible to provide data which will enable decision makers to determine whether or not the missile system meets stated requirements. Based upon test results using preproduction missile systems, AFTEC will have to provide a projection of the mature missile system's operational reliability. The effects of dormancy will have to be accounted for in that projection, and estimates will be further refined during the production and deployment phase of the missile system's life cycle.

2.4 TEST AND EVALUATION.

Test and evaluation may occur at any point in the missile system's life cycle to identify, assess, and reduce acquisition risks; to evaluate

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operational effectiveness and operational suitability; and to identify deficiencies in the system. During the conceptual phase, T&E may be accomplished to help select preferred alternative concepts. AFTEC involvement could include providing test results on similar missile systems. In the demonstration and validation phase, T&E is conducted to minimize design risks and demonstrate feasibility. The majority of T&E conducted during this phase will be accomplished by the contractor as components and subsystems are evaluated to make trade-offs that will satisfy design and operational requirements. As prototype or preproduction systems become available, some articles can be set aside to begin assessing the effects of dormancy on the missile system's reliability. IOT&E will be accomplished during the full-scale engineering development phase to estimate the operational effectiveness and operational suitability of the mature missile system. Those estimates will be refined as a result of FOT&E conducted during the production and deployment phase.

Obviously, the quality of initial reliability projections developed by AFTEC analysts will depend upon several factors including the availability of test articles and the length of the test and evaluation program. It is equally apparent that measuring the effects of dormancy on missile system reliability can require a long time relative to the time available for T&E prior to a production decision. Various techniques are available to the operational tester to permit development of a credible estimate of missile system dormant reliability early in its life cycle. Fundamental to their successful application is early involvement by the operational tester in the missile system acquisition and development process.

2.5 POLICY, GUIDANCE, AND DIRECTION.

This research effort has identified extremely limited guidance on the requirements for and the design and conduct of testing for dormant reliability. Reliability testing is addressed in a general sense under the cover of operational suitability in OMB Circular A-109, the DOD 5000-series directives, AFR 80-14, and AFTECR 23-1. MIL-STD-1388-1,

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Logistics Support Analysis, mentions dormant reliability by stating that the Logistics Support Analysis for reliability factors provides data for "...effects of storage, shelf life," The data input to the LSA comes from MIL-STD-785 reliability programs. This MIL-STD, Reliability Program for Systems and Equipment Development and Production, discusses administrative requirements and general guidance for reliability testing but provides no specific guidance for dormant reliability assessment.

Studies completed by RADC related to non-operating failures have consistently concluded that government documents establishing and supporting reliability requirements should be upgraded to include provisions for nonoperating mode reliability requirements and predictions. Degradation effects in various dormancy states (e.g., operationally ready storage, transportation and handling, launcher carriage, alert, captive carry) must be considered in addition to only those of the normally energized (active) state.

2.6 IS THERE A NEED?

The preceding discussions of the inherent nature of missile systems and the evolving maintenance concepts associated with them have indicated that dormancy is a major portion of a missile system's life cycle. Furthermore, the operational tester must provide an estimate of the projected mature missile system's operational reliability during the full-scale engineering development phase of the acquisition process. It follows that there is a need to assess the impact of dormancy on missile system reliability, and that need exists early in the acquisition process.

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SECTION III CHARACTERIZATION OF THE DORMANCY PROBLEM

3.1 GENERAL NATURE OF THE PROBLEM.

As discussed in the previous section, there is a need to assess dormant reliability and its impact on missile systems. The task or problem at hand is to develop methods that AFTEC may use to measure, predict, and assess dormant reliability and the effects of dormancy in the operational environment. One major aspect of the problem is the lack of consistent or well-defined methods in current practice which meet AFTEC's needs.

In reviewing the body of knowledge on the subject, one of the most noticeable facts is that the definitions employed by the various studies, reports, government documents, and reliability programs varied widely. This is more than just a definitional consistency problem. It is directly indicative of the differences in goals, purposes, and applications reflected by the literature. Data structures, sources, and the accounting which supports the data also vary widely and represent significant obstacles to comparison of results from different programs or studies, applying them to OT&E, and to the development of methodologies which could approach "universal" application.

With this brief introduction of the general nature of the problem in mind, the approach employed by this study effort is to modify/tailor existing approaches or develop new ones to meet AFTEC's needs while still tracking with the development process and the players involved. This is critical if AFTEC is to pursue early involvement in the weapons system development process and still produce meaningful results during test and evaluation from an operational environment perspective. The structure of definitions is such that ambiguity of data and data application may be reduced as much as possible and that results from early development processes may be related to later ones.

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Note that tailoring and developing new methodologies carries some risk in that the resulting approach may be untried or unproven. The development of the necessary methods is, in fact, still in its infancy. In this regard, some of the methods which are suggested later in this report should be viewed as having potential application and should be verified before being accepted as standard practice.

In the most general sense, the challenges presented by the dormancy problem are not really new but represent a specific example of a traditional AFTEC requirement--to assess and predict operational effectiveness and suitability early in the development process and before systems are fully fielded. The inherent perspectives of the players are also the same. The development contractor is concerned with inherent reliability while the user is concerned with field reliability. Inconsistent data reporting and time accounting has also been a persistent problem. The effects of given levels of reliability in the operational environment are generally not fully demonstrated until after OT&E. Thus there has always been a need for AFTEC to make projections to maturity. The same is true for dormant reliability of missile systems except that the time period between estimates and full field verification may be longer. Thus, in the general sense, the dormant reliability problem can be viewed as being a subset of the overall assessment and projection to maturity mission of AFTEC.

3.2 DEFINITIONS.

The definitions which follow are provided so that the specific problem of addressing dormant reliability and dormancy effects may be placed in the proper context. They also will provide a basis for interpreting the differences in the needs presented by OT&E requirements and other needs--such as those of the weapon system developer or contractor. Definitions which are in common usage by AFTEC are not presented herein unless there is a direct relationship to the dormancy problem, per se.

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The definition of dormant is presented last because it is built by using the other definitions in context. Alternate definitions of dormant which are in current usage are also provided so that the reader may see the logic involved in structuring a definition of dormant which can be utilized for OT&E purposes but which may also accomodate data from other phases of weapon system development.

3.2.1 All Up Round (AUR).

An all up round is a missile which, in its operational configuration, can be used in its intended combat role without installation of any parts, components, or subsystems. This definition applies to the missile itself and not to any launch equipment, pylons, or launch platforms. One possible exception is that the concept of operations for some missiles might require fins to be installed before usage. Such cases should be addressed on an exception basis.

3.2.2 Wooden Round.

A wooden round is defined as an AUR with "minimal" field maintenance. "Minimal" in this case is defined as a pre-selected list of on-equipment maintenance actions, depending on the maintenance concept. Wooden rounds are generally "checked" in the field and returned to a depot or other central location for all corrective maintenance. Incorporating a pre selected list of on-equipment maintenance actions into the definition allows a single definition to be employed with tailoring for specific missile systems. By using specific action taken codes to describe "minimal" field maintenance, data may be collected which captures the appropriate events. AFR 80-5/AFSC SUP 1, Figure A2-1, 12 April 1979, contains a good summary of on- and off-equipment maintenance actions.

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3.2.3 On-Equipment Maintenance.

AFR 80-5, Attachment 1, defines on-equipment maintenance as :

Maintenance actions accomplished on a complete end article (aircraft, drones, trainers, registered support equipment, photographic equipment, ground CEM equipment, special weapons, complete round munitions, uninstalled aircraft engines and L systems). This includes support general work (scheduled and special inspections, and so forth), removal and replacement of components, and fix-in-place repair actions.

For the purposes of this report a complete end article is considered to be an AUR with the possible exception that some missile engines (gas turbines, for instance) may be considered to be end articles. The reason for addressing on-equipment maintenance is that it is critical to the definition of dormant. There is some confusion as to the status of a missile during maintenance. In addition (as will be seen later) it is necessary to address dormancy at below the system level. Thus major subsystems are considered to be in a dormant status during on-equipment maintenance and not in a dormant status during off-equipment maintenance. The reasons for this convention are twofold. First, confusion is eliminated by considering a major subsystem to be restored to original specifications during off-equipment maintenance and thus considering the "dormancy clock" to be started over at the subsystem level. Secondly, ambiguity in data collection can be eliminated. This convention may be somewhat arbitrary but it does represent a reasonable compromise. In addition, wooden rounds can now be distinctly considered as a subset of all other missiles in terms of dormant reliability and the methodologies/data which will be used to address them.

3.2.4 Off-Equipment Maintenance.

AFR 80-5, Attachment 1, defines off equipment maintenance as: "In-shop maintenance actions performed on removed components, except complete aircraft engines."

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For the purpose of this report, "removed components" include all sub-systems (2 digit WUC) and below. The discussion of paragraph 3.2.3 applies.

3.2.5 Life Cycle.

The life cycle of a missile system is defined as the period of time from conceptual design through disposal of the system. It includes development, acquisition, operations, maintenance, support and all actions associated with taking the missile out of the inventory.

3.2.6 Life Cycle Profile.

A life cycle profile is a diagram or other representation of the states or status of a missile during its life cycle or any major segment of its life cycle.

3.2.7 Service Life.

AFR 136-1 defines service life as: "The length of time an item can remain installed in operating configuration or in actual usage." This definition would appear to apply to all items (explosive, electronic, etc.). The definition does not appear to mean the same thing as mean life, or mean time between malfunction, but implies the actual end of useful operation due to wearout. For the purposes of this report, service life is considered to be the length of time from which a missile is originally sent to the field until it is no longer in operational use.

3.2.8 Shelf Life.

AFR 136-1 defines shelf life as:

The length of time an item may remain in storage under prescribed packaging and storage conditions. The expiration date for shelf life on items with the

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month and year listed is the last day of the month.

Shelf life begins on the item's manufacture, cure, or assembly date.

This definition actually applies to items that cannot be brought back to the original specifications once they reach a certain age; e.g., film that degrades, powder that chemically decomposes, etc. It does not seem to apply to an electronic assembly that has a malfunction that can be repaired to retain its original specifications.

3.2.9 Operating.

Operating is defined as the state of a subsystem, assembly, or component when it is activated (as designed) by electrical or mechanical means at any level of stress. Operating is synonymous with "switch on." However, some care must be exercised when considering operating time for dormant reliability purposes. For instance, a rocket motor is operating when it is ignited. However, an electronic subsystem such as a guidance unit may be operating at various levels of stress when it is tested in a check-out procedure, during BIT, in captive carry, or in actual firing. At the subsystem level, if any portion of the subsystem is operating, then the entire subsystem is considered to be operating.

3.2.10 Non-Operating.

A subsystem, assembly, or component is considered to be non-operating when it is experiencing none of the electrical or mechanical stresses inherent in the (designed) activation of that subsystem, assembly, or component. It may however be experiencing stress caused by the environment, transportation and handling, captive carry G forces, etc. Non-operating time is a subset of dormancy and can be considered to be the time between subsystem activations.

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3.2.11 Storage.

Storage is defined as the state in which a system, subsystem, assembly, or component is zero percent activated and is in its normal configuration in a storage area. (Note that storage is a subset of non-operating.)

3.2.12 Inherent Dormant Reliability.

Inherent dormant reliability is that state wherein an AUR is maintained in a storage area and is totally non-operating. It does not include any maintenance or functional checks/BIT.

3.2.13 Operationally Ready Storage.

Operationally ready storage is that state in which an all up round is maintained in a storage area awaiting operational use. The AUR subsystems may be operating to the extent necessary to maintain the "ready" status for immediate use. The events of "operating" in a storage area should be rare, but depending upon design, it is necessary to include this possible state for an all-inclusive definition. For instance, a battery or gyro may be energized or activated in operationally ready storage.

It is important to note that operationally ready storage as defined herein is essentially the primary mode of "dormant" in the generic sense and is a central issue of dormancy. Because the common usage of the term dormant is so broad, it is necessary to define this new term. Inherent dormant reliability for an AUR could be considered to be non-operating operationally ready storage reliability. Dormancy effects, however, must consider a broader definition. If a specification were to state that a missile system must withstand a given period of dormancy and still be highly reliable, that statement might really be referring to a subset of the dormancy issue, namely, operationally ready storage. The other

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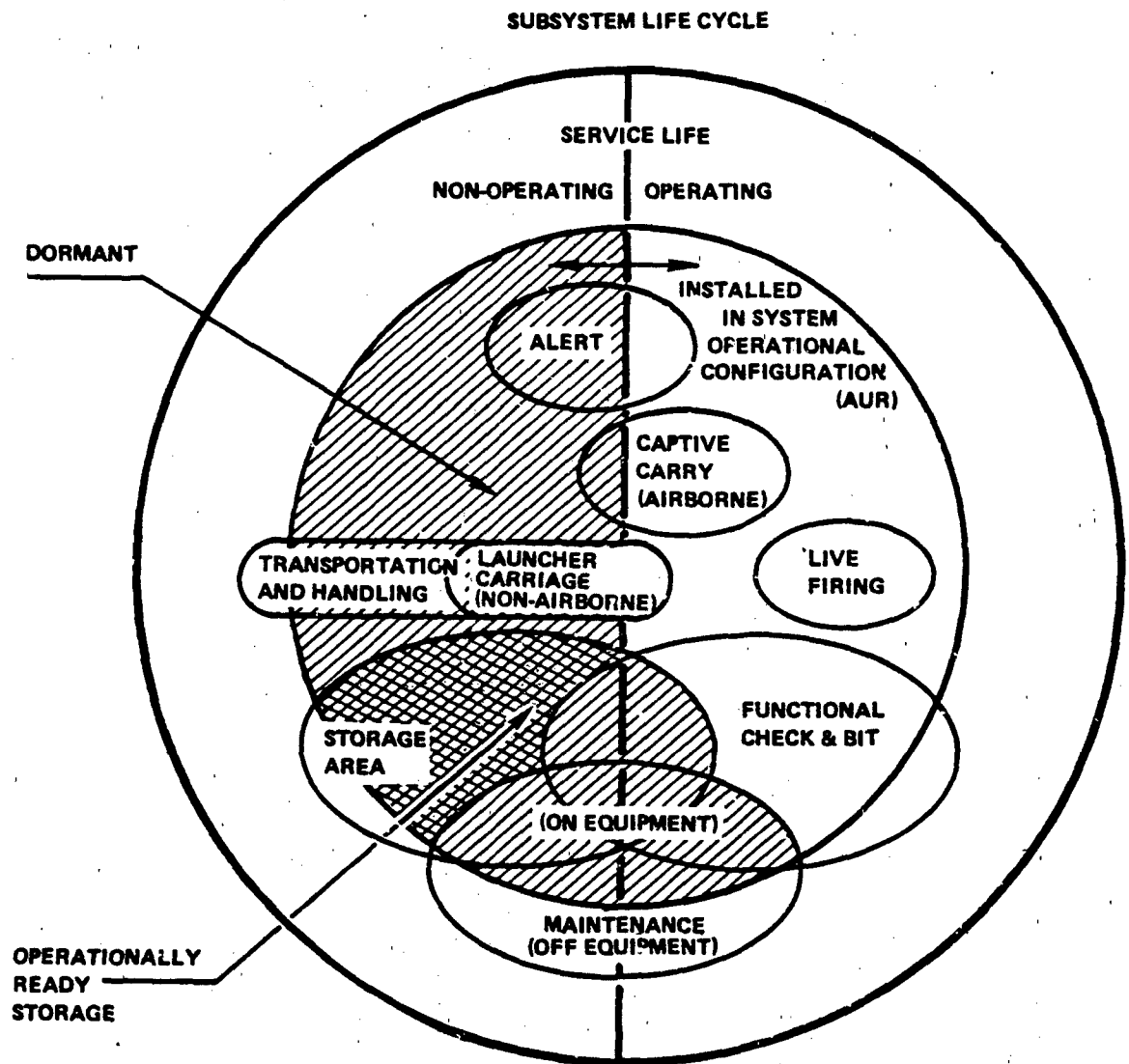
aspects that must be considered require that the term dormant be defined in the broader sense which follows.

3.2.14 Dormancy.

Dormancy is defined (for the purposes of this report) as those states wherein an all up round is not operating or is maintained in operationally ready storage including all on-equipment maintenance and functional checks/BIT necessary to maintain the desired status. Dormancy includes the non-operating portions of alert, captive carry, transportation and handling, and launcher carriage. Non operating refers to subsystems which are installed in an AUR. A Venn diagram of this definition is provided in figure 2. Note that dormancy is defined at the subsystem level, but requires that those subsystems be installed in an all up round. This concept is logical in that some subsystems may be totally inactive (rocket motors, for instance) while other subsystems (such as guidance units) may be operating during various phases of the missile's life cycle prior to actual firing. In addition, some missile systems (air-to-air in particular) may rotate through various operational postures--operationally ready (O.R.) storage to alert, back to O.R. storage, captive carry, and back to O.R. storage, etc. Strategic systems may spend long periods of time in an alert status with guidance systems operating and the remainder of the subsystems totally inactive.

The operationally ready storage mode is predominant in that this state is where "long periods" of dormancy accrue. The ability of a system to withstand these "long periods" may be influenced by relatively short periods of operating time or the stress inherent in other states such as transportation, captive carry, or launcher carriage. Conversely, the ultimate operational reliability is influenced by the system's ability to withstand "long periods" of dormancy. Thus, a synergistic relationship exists when all possible states and the interactions among them must be considered.

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BDM-A-61-016-TR

Figure 2. Dormancy: Subsystem Level, Based on Subsystem Installed in AUR, Nonoperating Time, on-Equipment Maintenance, and Functional Checks/Bit in Storage (Includes Operationally Ready Storage as a Subset)

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3.2.15 Alternate Definitions of Dormancy.

The following definitions are in current usage and are provided for purposes of contrast.

3.2.15.1 Alternate Definition 1.

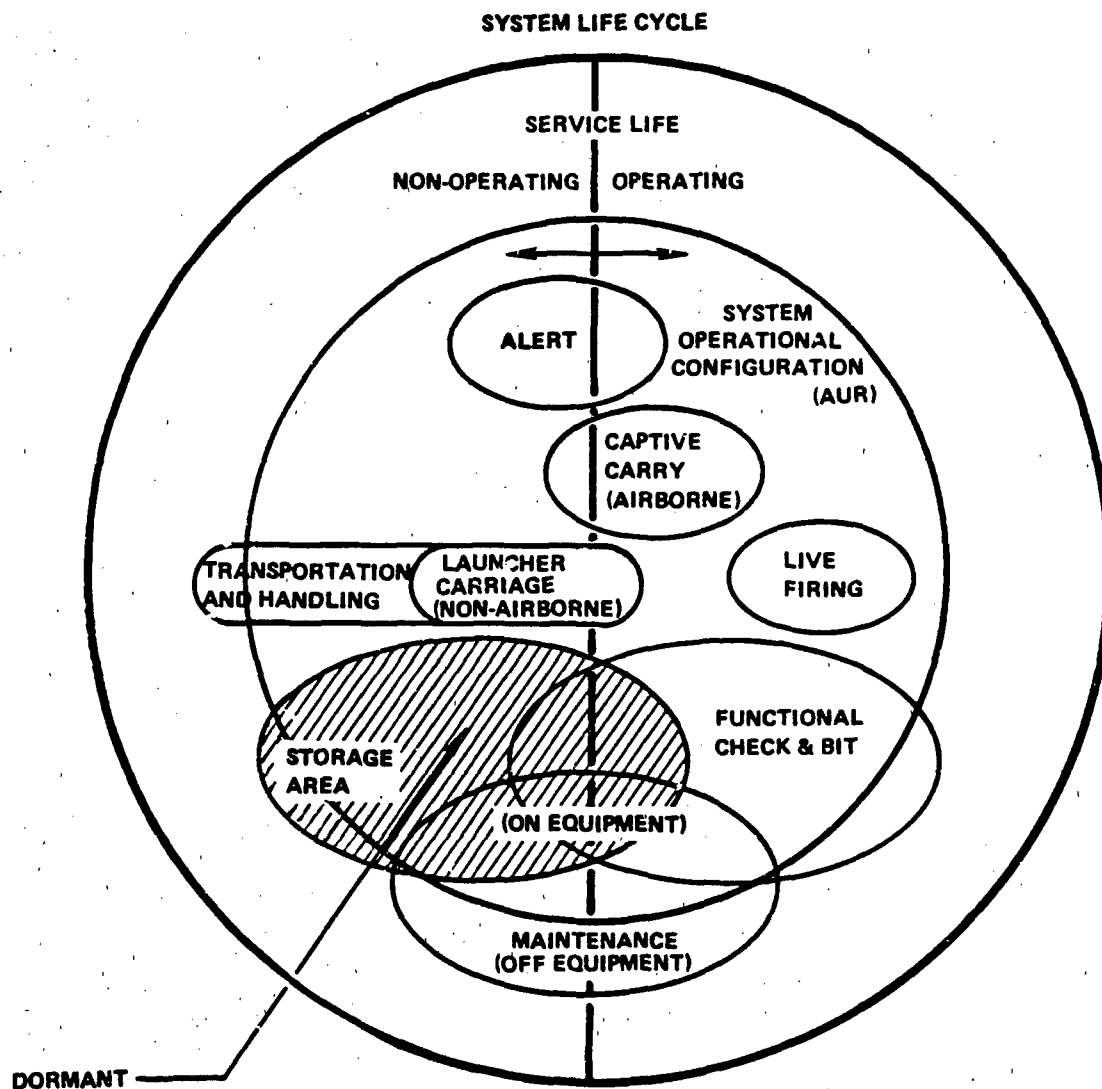
Dormancy is the state in which a system, subsystem, or component is between zero and 10 percent electrically energized and is in its normal configuration for operation but in a storage area. A Venn diagram of this definition is provided in figure 3. Close examination of this figure in light of the previous discussion will highlight some obvious deficiencies. Components and piece parts in storage are included. Although the literature (see references 18 and 29) shows no statistical difference between the failure rates for systems that are dormant or parts (from those systems) that are in storage. It is virtually impossible to track components or parts from storage all the way through installation in an AUR in terms of elapsed time. The arbitrary 10 percent electrically energized limit also presents some problems. As discussed earlier, some subsystems may be fully operating while others are fully non-operating within the same missile at a given point in time. Finally, there is no provision for handling the synergistic nature of dormancy.

3.2.15.2 Alternate Definition 2.

Another definition in current practice is as follows:

Dormancy is the state wherein a device, a component, or a part is connected to a system in the normal operational configuration and experiences below normal or periodic structural, mechanical, electrical, or environmental stresses for prolonged periods up to five years or more before being used in a mission.

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BDM-A-81-016-TR

Figure 3. Alternate Definition 1: System, Subsystem and Component Level, Based on Storage Area \leq 10% Energized

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As before, a Venn diagram of this definition is provided in figure 4. This definition is realistic except it is obviously very difficult to determine how much "stress" is appropriate. The difficulties of consistent tracking through a data system are obvious.

3.3 DORMANT RELIABILITY.

Reliability can be considered to be the probability that an item will remain failure free over a specified period of time (or be in a failure free state after a specified period of time). In considering dormant reliability, the same definition of reliability applies except that "over time" covers several possible states which exhibit potentially different failure characteristics. Thus a full treatment of dormant reliability must consider all possible states--inherent dormant reliability, operationally ready storage reliability, non-operating transportation and handling launcher carriage reliability, and non-operating captive carry reliability.

3.4 DORMANCY EFFECTS.

The effects of dormancy in missile systems must be considered at several levels and in a hierarchical sense. The usual failure modes and effects analysis (FMEA), which is accomplished early in the missile system's life cycle, is at the very lowest level in the hierarchy. A discussion of dormancy effects and the causes of system reliability degradation at the more traditional FMEA level is provided in annex B. Second in the hierarchy is the fact that dormancy effects a given level of reliability. Dormant reliability effects, in the context used in this discussion, must reflect the implication or ultimate impact upon operational reliability. From an AFTEC perspective, it is necessary to recognize the difference between logistics and operations effects.

The effects of dormant reliability on logistics are more closely representative of traditional FMEA but only in a limited sense. The

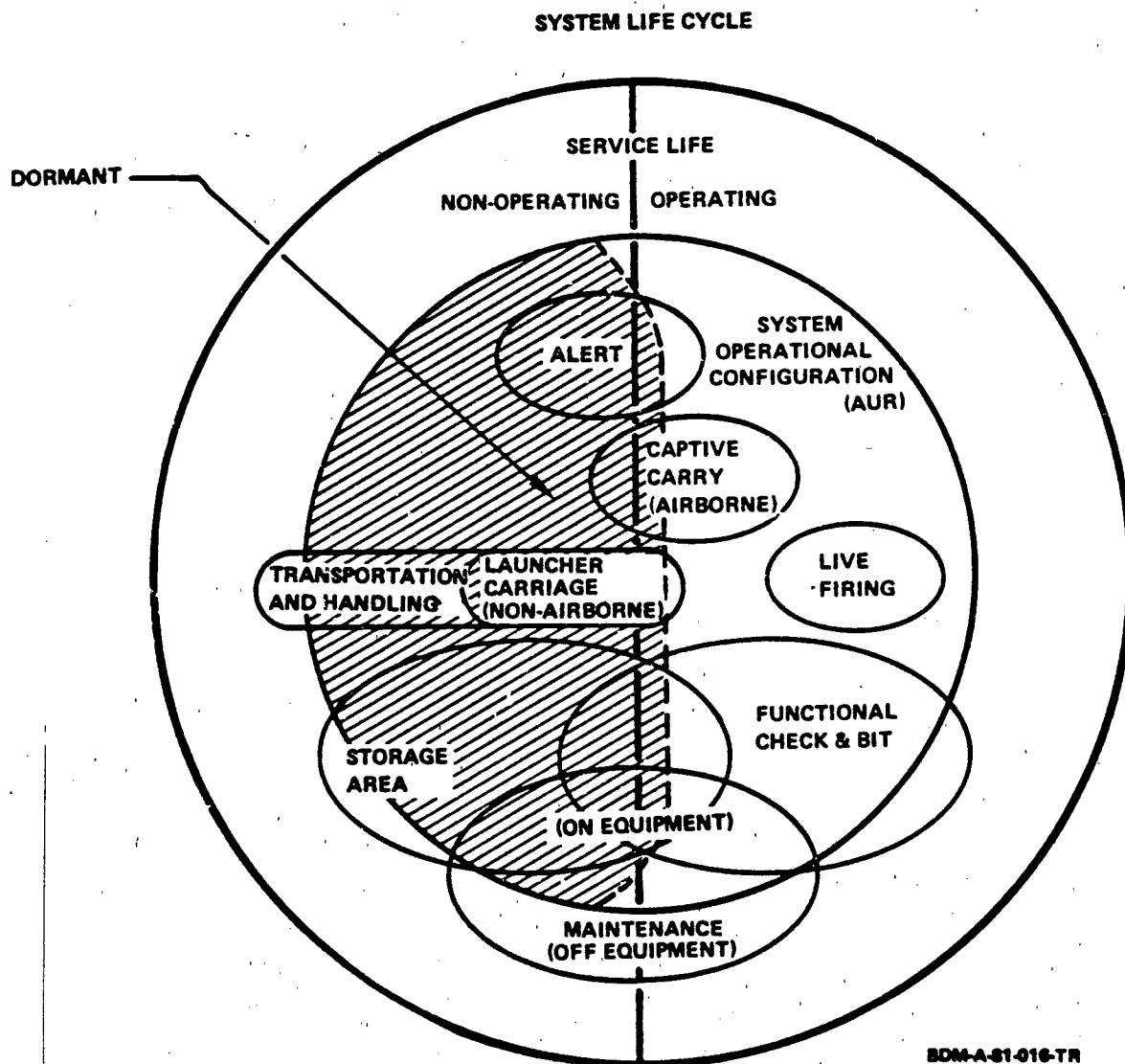


Figure 4. Alternate Definition 2: System Level, Based on AUR with Less Than Normal or Periodic Stress

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logistics system will be concerned with all types of failures (i.e., Type 1, 2, and 6) because the impacts are not significantly different. Required spares provisioning, manpower requirements, and their associated costs throughout the missile system's life cycle are affected by dormant reliability and must be correctly estimated if the missile system is to be adequately supported. The effects of dormant reliability on operations are more closely related to the capability of the missile system to function effectively. Basically, not all "failures" are critical. Those which certainly affect operations; those which are not may impact operations, but they directly affect logistics.

The task for the operational test analyst is to determine those failures which directly affect operational capability. For example, suppose a certain seal tends to dry out and crack after prolonged periods of dormancy. An FMEA would conclude that hydraulic fluid leaks because the seal cracks. The logistics analyst would conclude that more spare missiles will be required to support the wooden round maintenance concept because the hydraulic actuation system leaks during storage. The operations analyst will conclude that the missile will probably miss the target because the hydraulics system fails to drive the control surfaces. The effects of dormancy must be addressed at a level which permits estimation of their impact upon operational effectiveness.

3.5 INHERENT LIMITATIONS.

Several limitations inherent in the nature of the dormancy problem are worthy of mention. First, it is extremely difficult to know when a failure has occurred. Unless there are fairly frequent checks performed, a failure may not be detected until a missile is put to an operational "test" or actual live firing. If, for instance, several years have elapsed during a dormant period and the missile then fails to operate as intended, when did the failure occur? Second, it is well known that checking a missile may cause a failure. In fact some manufacturers limit the number of functional checks or BITs in their warranty. Third, it is

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generally difficult to tell what caused failures--age, transportation stresses, manufacturing defects, induced maintenance failures, etc. Measuring dormant reliability then poses a different sort of problem than the typical operating system in test and evaluation. In addition to these aspects, data systems are not structured to capture the elements necessary for testing or validation nor do they accurately account for time or age--factors central to the dormancy issue.

3.6 LIMITATIONS ASSOCIATED WITH CURRENT APPROACHES.

The current "state of the art" is not directly applicable to the OT&E environment. Most of the existing methodologies are oriented toward the development contractor's or SPO's needs and are concerned with developing, predicting, and validating accomplishment of specification requirements. In addition, they are geared to inherent reliability as opposed to field reliability and are almost always accomplished at the piece parts level. When adjustment factors (or K factors) are developed to account for the lack of operational reality, they are often "backfitted" to meet the specification or get the right answer. In addition, K factors, as will be seen later, are highly system dependent and generally are applied at the piece part level. Even the better known and documented surveillance programs (IHAWK as discussed later) have failed to isolate the causes of reliability degradation among aging, transportation, test equipment and procedures, and environment. In addition, traditional surveillance programs are oriented toward engineering "fixes" (by lot). There is nothing wrong with this goal, except that it does not directly assist in OT&E or projections to maturity.

3.7 ITERATIVE AND LONG TERM NATURE OF THE PROCESS.

With the previous discussions in this section as a background, it is obvious that there are no ready made solutions to the dormancy problem. Actual measurement of dormant reliability is a long term process -- 10

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years or so--and one which will require many test assets. These, unfortunately, are luxuries that AFTEC can generally not afford.

The logical conclusion then, is to pursue the development of early estimating projection methodologies (even rules of thumb) and test methodologies that can be improved over time. In addition, AFTEC involvement and coordination with all of the system development players is essential so that early program data, tests, and surveillance programs can be structured in a mutually supportive way. Finally, detailed knowledge of other methodologies, even though they might not be applicable to OT&E, and knowledge of missile systems at large are both necessary if "experience" is to be iteratively applied toward improving the process.

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SECTION IV EXPERIENCE AND THE "STATE OF THE ART"

4.1 CURRENT METHODOLOGIES.

Current techniques for estimating dormant reliability generally fall into three rather broad categories of analytical prediction based upon parts count and stress, failure rate modification factors, and testing. Each of these broad technique categories has advantages and disadvantages which would warrant the cautious use of their results in a dormant reliability assessment program. Current dormant reliability prediction techniques are typically applied during the design and early development phases of the missile system's life cycle and may not be directly applicable in an IOT&E program. However, the operational tester will have access to data generated by the developer, and an understanding of the general nature of the data will be necessary if it is to be used in the operational reliability projection.

4.1.1 Parts Count and Stress Analysis Prediction.

MIL-HDBK-217C, Reliability Prediction of Electronic Equipment, provides two methods of reliability prediction for electronic parts. Both methods are applicable during the design phase of the system although they require different degrees of information to apply them. They provide a basis for reliability predictions during acquisition programs for military electronic systems and equipment. Both methods are summarized here; more detailed discussions are provided in annex A.

The parts count reliability prediction method assumes that the equipment failure rate is a function of the failure rates of its components or parts. The information needed to apply the method is generic part type and the number of such parts in the equipment, the quality level of the part, and the equipment environment. This prediction method is applicable during the early design phase and is generally used during bid proposal since it permits relatively easy comparison and evaluation

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of alternative proposed concepts. It should be noted, however, that failure rates derived using this method may apply only if the entire equipment, i.e., all of the generic parts, is to be used in one and the same environment. If not, then the method should be applied separately to portions of the equipment in each environment. The total equipment failure rate can then be estimated by adding these "environment-equipment" failure rates which have been scaled using appropriate environmental factors. The current MIL-HDBK-217C provides factors for 11 different environmental states. A recent update has expanded the list to 23 environmental states.

The part stress analysis prediction method requires a greater amount of detailed information and is applicable during the later design phase where actual hardware and circuits are being designed. Part quality, environmental stress, thermal aspects, circuit and package complexities, densities, and connections are factors which are accounted for in this method. MIL-HDBK-217C provides reliability prediction models for various categories of electronic components to be used for estimating both operating and non-operating failure rates. It is not likely that the operational tester will employ this prediction method to estimate dormant reliability, but the missile system being developed will probably base early reliability predictions on this technique.

4.1.2 Failure Rate Modification Factors.

Numbers which are used to modify failure rates to account for varying stresses imposed by different applications and environments are generally known as K factors. They are used and misused to adjust a basic rate experience for hardware when directly applicable experience data are not available. Factors have been developed and applied at all levels from generic parts to total systems. Success in these efforts has also varied as is evidenced by the following examples.

Derr, Van Hoorde, and Girdis (reference 33) used failure rate data from several different military system programs to develop a method of predicting MOS/LSI failure rates in automotive applications. Unfortunately, although the prediction model was based upon derivations from

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empirical data sources, verification of the model was not possible due to insufficient history of LSI devices in the automobile.

Boeing (references 84 and 85) provided a technique for developing K factors at equipment and LRU levels using field experience data. Equipment classes included mechanical/hydraulic, electromechanical, electronic, and battery. Applications considered were ground, ship, satellite, and aircraft. This method, by using actual field experience data, developed factors to "fit the data" at the individual LRU level. By combining LRU-level factors for each of the primary equipment classes, an average K factor was obtained for each class-application. These factors were then "validated" against empirical field data and revealed that a ball park estimate could be obtained within each equipment class.

General Dynamics (references 82 and 83) developed K factors based on estimated environmental severity for use in the Ground Launched Cruise Missile Squadron Operations and Maintenance Simulation Model. Factors were obtained for the missile, transporter-erector-launcher, and launch control center for 15 different environments. The K factors were used to normalize all environments to the comparative base of dormant storage. The validity of the K factors used in this effort must await failure rate data from field experience with the GLCM weapon system. It is interesting to note, however, that reliability predictions obtained with this approach equal or exceed stated requirements.

As a final example, Shelley and Stovall (reference 32) provided insight into the problem of predicting field reliability performance from MIL-STD-781 laboratory test results and, conversely, the problem of translating required operational levels of field reliability into comparable quantitative levels to be demonstrated in the laboratory. Fifteen specific factors and a general one (i.e., all other differences) were identified that contribute to differences between laboratory and field achieved results. The study examined data for 35 major C-5A equipment items, but the results could not conclusively show that the translation between laboratory and field data could be improved by the use of K factors.

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What, if any, conclusion(s) can be drawn from documented experience involving development and application of K factors? K factors are only a tool. Failure rates derived from applying K factors should be less accurate than rates derived from directly comparable experience. K factors probably have more applicability at the part or component level and will continue to be used by system developers as the basis for building higher level (i.e., equipment, subsystem, etc.) K factors. At best, K factors may provide ballpark relationships between application environments.

4.1.3 Testing.

Testing provides the mechanism for obtaining empirical failure rate data. There are two driving considerations in any test program: sample size and required time. The sample size which must be used to establish a high reliability at a reasonable confidence level is generally prohibitive in a real world situation. From an operational viewpoint, the necessary sample may be unattainable early in a weapon system's life cycle since there are limited quantities of pre-production systems available, and they may not be representative of mature production systems. The time available for accomplishing a comprehensive test program is finite and limited and may not be compatible with the estimated time required to accomplish all necessary testing. Testing can be accomplished in real time or in an accelerated manner.

4.1.3.1 Accelerated Testing.

Accelerated or overstress testing is a common method used to obtain failure rate data in a relatively short time period. It requires a knowledge of the predominant failure mode under rated stress conditions, the environment which excites the failure mode, and a quantitative relationship between the level of the stress environment and the rate of occurrence of the failure. Once this relationship is obtained, it can be

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used to determine an estimate of the failure rate within the application environment of interest. Accelerated testing can be an effective method of obtaining part, component, or subsystem level failure rate data.

Part screening is a form of accelerated testing applied during the infant mortality phase of the equipment's life. A more detailed discussion of screening methods is provided in annex E. Its purpose is to compress the early failure period and reduce the failure rate to acceptable levels as quickly as possible. It is assumed that inferior devices will fail and superior devices will pass provided the tests and stress levels are properly selected. The operational tester, when using data obtained from screening, should recognize that it may exhibit an abnormal failure rate which must be accounted for in any reliability prediction.

Microcircuit devices exhibit a catastrophic failure rate which decreases linearly with the reciprocal of the absolute junction temperature. It has been shown (reference 29) that use of the Arrhenius model is acceptable for applications in aging processes in which temperature is the only accelerating factor. The Eyring model is somewhat more advanced and accounts for two accelerating factors: junction temperature and applied bias voltage. Neither of these techniques have been proven to be exact models of the time-stress combination with respect to failure rates. However, they are reasonable approximations when applied within the bounds of specified conditions.

Solid rocket motors are subjected to accelerated environmental testing at the Naval Ordnance Station, Indian Head, MD. The facility provides environmental (e.g., temperature) changes at twice the expected seasonal rate. Results of the 2 to 1 testing have correlated closely with similar failure rate data obtained from field experience. The correlation has been qualitative to date; no rigorous mathematical comparison has been accomplished.

Power on/off cycling has been shown to have a definite adverse effect upon electronic equipment reliability. Accelerated power on/off cycling has an overwhelming tendency to induce failures in the open mode

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and appears to be particularly effective in precipitating poor conductivity fault points (reference 18). The incidence of power on/off cycling failure rates was correlated with dormant failure rates for various components and indicated that a single power on/off cycle can be as much as 1,000 times more stressful or effective in causing failures than 1 hour of dormant time. However, the results were highly component-dependent.

Accelerated testing has been a very effective method of reducing the time required to accomplish the magnitude of testing necessary to provide a statistically significant measure of reliability on low failure rate items. The literature research has revealed that accelerated testing has generally been restricted to components. Several problems are encountered when accelerated testing principles are applied to a complete system or even to reasonably complex subsystems or subassemblies. The foremost problem is determination of the acceleration factor. Acceleration factors have been validated at the part level by testing at various stress levels. However, at the system level, it is highly unlikely that validation of applicable acceleration factors could be achieved. A second related problem has to do with failure mechanisms. If individual parts are sensitive to different stresses, it would not be reasonable to expect that a single stress could be chosen to provide an accelerated test. This research effort has failed to identify any documented evidence of successful system level accelerated testing.

4.1.3.2 Real-Time or Surveillance Testing.

Testing which is not accelerated is typically accomplished in real time and, with respect to reliability testing, is generally referred to as surveillance testing. It is a detailed test, analysis, and reporting program to compare a missile system to established standards for projecting shelf and service life throughout its life cycle. In the broadest sense, it includes screening and other forms of accelerated testing discussed earlier, acceptance testing, and both developmental and operational testing. However, in the more traditional sense a surveillance

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test places a specified number of preproduction or production missiles in actual or simulated field storage conditions. Periodically, selected samples of these assets are removed from storage and examined for degradation from original specifications. The examination may include BIT, disassembly and inspection, or live firing. Typically, surveillance programs are designed to provide engineering fixes for the missile system and not necessarily to provide the operational tester with a ready method for predicting mature system operational reliability. The surveillance program's value to the operational tester lies in the availability of similar system data upon which to base a comparability analysis when developing an early system reliability prediction. Several surveillance test programs exist and provide potentially usable information. A sampling of those programs is included in the next section.

4.2 EXAMPLES OF SPECIFIC EXPERIENCE.

4.2.1 TOW, MGM-71.

The TOW is an anti-armor missile used by infantry personnel. It is tube-launched, optically guided, and controlled by wire. The Army began a 10-year test program in 1976 to determine the storability of the missile. Each year 60 missiles are checked, and failures/malfunctions are analyzed. The missiles to be tested are obtained from the Canal Zone, Alaska, Arizona, and Alabama. Thirty-two parameters of missile electronic units (MEU) are recorded and plotted. Sixteen of the 60 MEUs tested each year are retained for future testing. Hence, the number of MEUs available for testing increases each year, and there will be 160 MEUs in test/storage at the end of the 10-year test period. After 3 years of observation and testing, no parameter drift trends have been detected, but it has been determined that handling and manufacturing errors have accounted for most of the 50 failures which occurred in the 180 missiles tested. None of the failures were considered mission critical, i.e., they would not have resulted in an in-flight failure or degraded missile performance.

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4.2.2 MAVERICK, AGM-65.

The MAVERICK is an air-to-ground, electro-optical guided missile for tactical fighter aircraft. Ogden Air Logistics Center has complete engineering responsibility for the missile. The ALC has an ongoing test program and provides quarterly reports of missile failures detected during testing. To date, 25,000 missiles have been manufactured and stored; 4,161 have been tested. At the present time, the hydraulic actuator system (HAS) of the missile has a higher failure rate (leaks which would not necessarily abort the missile) than the guidance and electronic units. It has been found, however, that after the HAS leaks have been repaired, by either shop or field personnel, the failure rate doubles. The mechanical part of the HAS is subject to time degradation of reliability, but the degradation is not significant. Some gimbal bearings have "frozen up" because of lubricant runoff. The guidance unit has exhibited no age related failure trend. The entire missile has exceeded its specified reliability. Current system storage reliability is 90 percent; the specified was 80 percent. Present flight reliability is also near 80 percent. The inspection frequency may be reduced because of this high reliability; inspections were at 12 months, then 24 months. At present, 36 months is being considered.

4.2.3 COPPERHEAD, M-712.

The COPPERHEAD missile is a cannon fired projectile which is guided to its target by a laser designator. The Army is procuring these missiles in large quantities to be stored worldwide. A surveillance test program will be established to detect and fault analyze each malfunction. The program is called Storage Reliability Verification Test (SRVT) and is composed of four parts: Baseline Analysis, Accelerated Aging Tests, Real-Time Aging Tests, and Real-Time Field Aging Tests. Baseline analysis will completely analyze two electronic and two electrical parts for electrical, physical, and mechanical properties to form a baseline. Data

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from various sources will be gathered and analyzed to determine the environment to which the electronic parts will be subjected for accelerated aging tests. The initial estimate of the average acceleration factor for an environment of 85°C, 85 percent relative humidity, and effectively 0 PSIG, is 44. The plastic packaged COPPERHEAD integrated circuits are being subjected to this environment to validate or modify the estimated aging factor of 44. Seven samples will be drawn from the first acceptance lot of each part type for real-time aging tests. Two will be used for baseline and five others will be stored in real-time storage. The storage will be in a plastic bag at room ambient temperatures and conditions. Every 6 months the items will be removed and tested for each baseline parameter. Real-time field aging tests will be conducted on all up rounds. A total of 16 projectiles will be stored at various locations in the CONUS. Each location will provide a different environment, but all projectiles will be in open storage. Every 6 months the rounds will be returned to the factory for functional tests. Failures will be analyzed and trend analyses will be accomplished. Also, all of the 386 engineering development missiles will have storage data collected for analyses.

4.2.4. ALCM, AGM-86.

The ALCM is currently undergoing follow-on test and evaluation (FOT&E) at Edwards Air Force Base, California. One of the major objectives of the test effort is to measure and estimate the reliability of the ALCM. However, because of limited resources and time, direct dormant reliability testing or measurement has not been attempted. Rather, a procedure for projecting the dormant, or non-operational, reliability from operational failure data is being used. This procedure involves the projection of operational reliability to mature system operations and a K factor multiplication to convert projected operational reliability to projected dormant reliability.

The ALCM test team has partitioned the total time ALCMs spend under test into five phases: ground inactive (GI), captive inactive (CI),

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ground active (GA), captive active (CA), and free flight (FF). All ALCM failures, to include Types 1, 2, and 6, have been recorded as have total operating time and total possessed time. An attempt has been made to partition the observed failures into the phase each ALCM was in when the failure occurred. However, uncertainties arise when an ALCM is transitioned from a non-operating state to an operating state during verification testing or flight operations. A failure that is detected at these points cannot, under certainty, be classified as having occurred during the non-operational period or as having occurred when power was applied. To remain on a conservative estimate side, therefore, when calculating an estimated operational MTBF for the ALCM, the total number of failures that have occurred in all phases is used. Thus:

$$MTBF_{(operational)} = \frac{\text{Total Operational Time (CA, GA, FF)}}{\text{Total Failures All Phases (CA, GA, FF, CI, GI)}}$$

Total operational time for the ALCM has been defined simply as "power-on" time or active time. The failures that are counted in the denominator are all Type 1 failures plus all mission critical Type 2 failures.

The procedures used in estimating the dormant reliability of the ALCM are as follows: (1) calculate the most current operational MTBF using only Type 1 failures in the denominator, (2) project the calculated reliability to mature system operations (2 years after IOC) using the Duane projection technique, and (3) use a system level K factor to convert the operational reliability estimate to a dormant reliability estimate.

Because of perceived differences in the characteristics of the ALCM engine and the rest of the ALCM, the engine reliability estimation is handled separately. The same estimation procedure is used for the engine; however, the reliability growth rate and K factor used are different and apply to the engine only.

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4.2.5 I HAWK, MIM-23B.

The Improved HAWK Missile Stockpile Reliability Assessment Program represents one of the most comprehensive surveillance programs in existence (reference 81). It also appears to be one of the most successful and is being used as a basis for structuring similar programs for new missile systems. Because the IHAWK might well be considered the state-of-the-art in surveillance testing, its surveillance program is described in more detail than those of the preceding sample programs.

The basic HAWK Missile System developed and deployed in the latter part of the 1950's contained an electron tube missile guidance section. The maintenance test concept employed at that time required the missile to be disassembled, tested, and repaired in the field under varying environmental conditions. The exposure of missile guidance section critical components to various environments, numerous tests of the missiles during their useful life, extended run-cycles during standby alerts, and workmanship of field personnel during repair and application of MWOs, caused a large number of induced failures. The overall in-flight reliability of the basic HAWK Missiles during ASP was less than 65 percent even though the missiles were "checked out" immediately prior to firing.

When the Improved HAWK Missile design was contemplated, elimination of all of the foregoing, undesirable, operational characteristics were given a high priority with the intent of "designing them out" of the system. Those design considerations resulted in a solid state electronics guidance section (package) with the inherent qualities of extended component life and greater component stability. Reduced operating time, elimination of field testing, and curtailment of any missile disassembly and modifications in an uncontrolled field environment were added as operational constraints. The expected operational life of this new missile design was initially estimated as 5 years based on the individual component aging characteristics, stability, and reliability. The new missile design and use-concept eventually came to be called the Certified Round Missile.

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Improved HAWK Missiles are produced in discrete blocks or production lots. Acceptance and initial certification of a production lot of missiles is not made until completion of lot acceptance flight test, and is based on all of the process production tests, including 100 percent static test of guidance packages as well as the flight test data of sample missiles. The initial certification starts at the piece part level and continues through final assembly of the missiles. After missile guidance packages are assembled to GFE components, a sample of missiles from the lot is randomly selected for lot acceptance firing tests. A minimum of three missiles and up to twenty missiles may be fired before the production lot is "accepted" or "rejected." The lot acceptance flight tests are designed to require that the missiles accomplish intercept on a variety of target parameters. The specified levels for reliability and lethality must be met.

Once the missile lot has been accepted, it is deployed to operational field units. As the missile changes location or status, field units record the changes and provide the information to the data base. No maintenance is performed by the field units, the missiles are not operated until flight, and they are not subjected to testing in the field.

Each year a random sample of each missile lot is tested at Theater Readiness Monitoring Facilities (TRMF) around the world to evaluate degradation in missile readiness due to handling, aging, and environment. Each missile returned to the TRMF is subjected to a series of tests identical to those performed at the factory. The test results are transmitted from the TRMF to the deployment data bank where all lot information is used in a comprehensive trend analysis to provide readiness assessment and to indicate possible future trouble areas.

The system described above has effectively maintained the readiness posture of the fielded IHAWK Certified Missile over the past 8 years to the extent that no firing battery has entered a Red Status due to lack of ready missiles. This favorable readiness posture and a missile with higher in-flight reliability has been achieved at a substantial cost saving, when compared to the Basic HAWK experience.

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4.3 SUMMARY.

Current methodologies for projecting missile system operational reliability early in the system's life cycle tend to focus at the part level. Prediction techniques rely on parts count and part stress analysis methods. The expanding use of K factors to adjust or modify failure rates to account for varying stresses imposed by different applications and environments also seem to be more appropriate at the part level. Applicability at the system or even the major subsystem level requires further study and development. Accelerated testing techniques are also tailored to part testing. In fact, it is doubtful that accelerated testing could be effectively applied at the system level without significant additional study and analysis. Surveillance testing can also provide potentially useful data, but it will generally come from a similar program.

There are many sources of useful data for the operational tester to use when developing early predictions of a new missile system's operational reliability. However, extreme caution must be exercised to ensure that the nature of the data (e.g., source, derivation, similarities/dissimilarities, etc.) is thoroughly understood.

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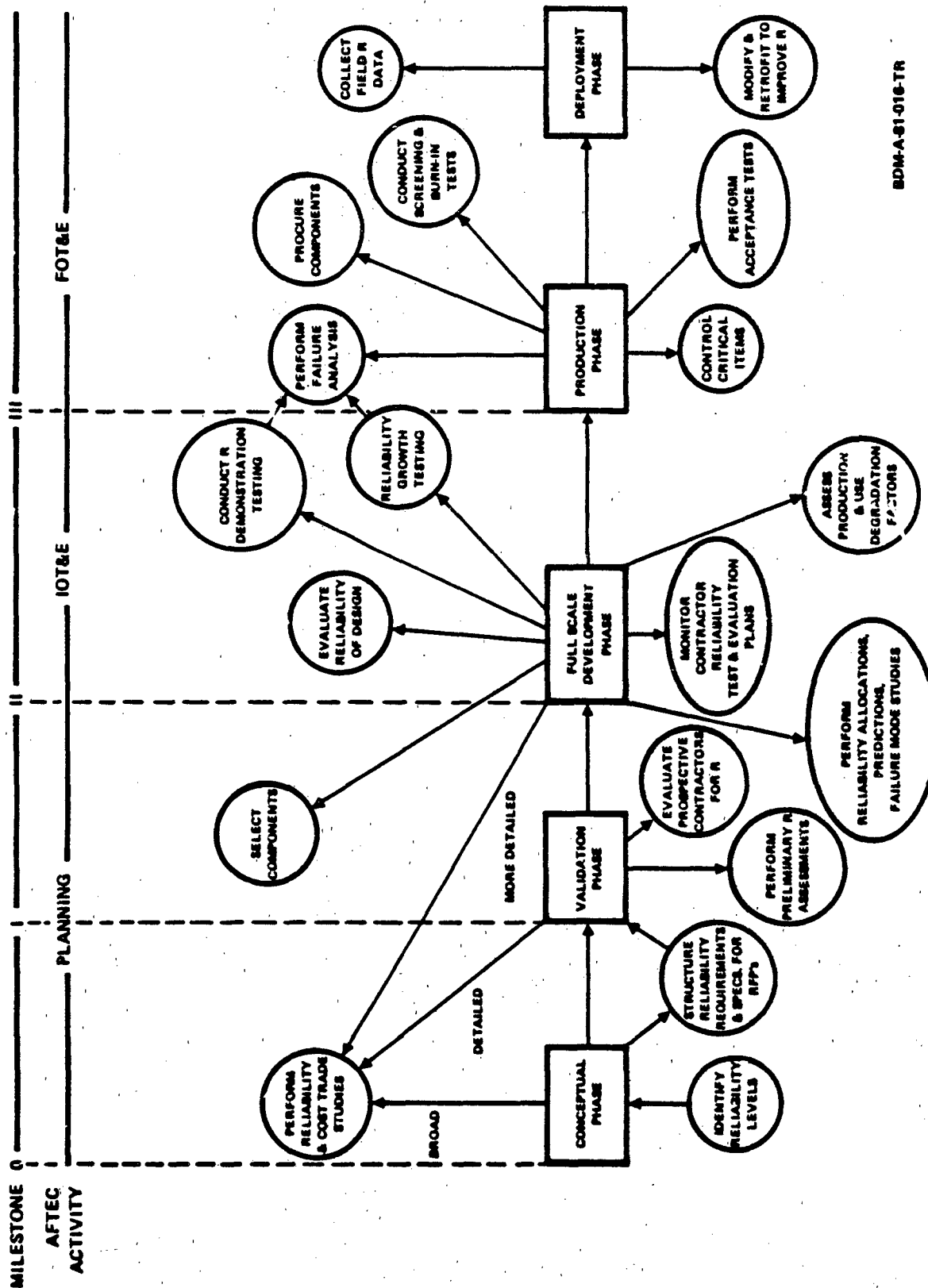
SECTION V NECESSARY CONSIDERATIONS AND PREREQUISITES

5.1 ACQUISITION PROCESS CONSIDERATIONS.

The weapon system development process was briefly outlined in section II. Figure 5 provides an indication of relationships between reliability life cycle activities and the various phases within the acquisition process. Major milestone decision points are also shown. The weapon system acquisition process and the associated role of the OT&E agency are described in AFM 55-43, and there is little which can be added to that discussion. It is readily apparent, as revealed in figure 5, that a great deal of information is available to the operational tester early in the missile system's life cycle.

The AFTEC planning process will usually begin at or near Milestone 0 and continue beyond Milestone II to the start of IOT&E. Early in the conceptual phase, reliability specifications will be formulated by the developing command from the using command's operational requirements. Depending upon the quantity and quality of information available as input to the dormant reliability assessment approach described in section VIII, some initial insight into dormant reliability requirements could be obtained during the conceptual phase. Throughout this initial phase of missile system development, the system program office (SPO) and the developing contractor(s) will comprise the principal sources of data to be used in the reliability prediction process. The data, however, will generally be limited to specifications and preliminary designs.

As the program progresses into the validation phase, data should be available from failure modes analyses, design reviews, initial reliability evaluation tests, and failure analyses. Again, the SPO and contractor will be the sources of the information. From the operational tester's viewpoint, the useability of the data will depend upon his understanding of how it was obtained. Initial estimates of test and support resources necessary to accomplish IOT&E must also be identified during this period.



BDM-A-81-018-TR

Figure 5. Reliability Life Cycle Activities

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During IOT&E, operational failure rate data will be available, and some dormant failure rate data should be available from the surveillance program. That assumes, of course, that the surveillance test program was initiated during the planning phase. AFTEC involvement in the missile system's life cycle may well extend into at least the initial phases of FOT&E. The types of data available to the operational tester are not unlike that which are obtained during IOT&E. Again, however, the nature or characteristics of the data may be different and must be thoroughly understood. Principally, failure rate data will be obtained from production missile systems which are employed by the using command under conditions more representative of the expected operational environment. As in IOT&E, failure data will include both inherent and induced failures. Dormant failure data from the surveillance program should also be available. Caution is advised early in FOT&E because of the potential differences in missile systems. While production missiles may be providing operational failure rate data, similar data obtained from the surveillance program may be based upon preproduction or early production missiles.

5.2 SYSTEM SPECIFIC CONSIDERATIONS.

The preceding discussion was intended to provide a rather brief overview of the basic phases in the weapon system acquisition process, the principal players (from an operational tester's viewpoint) in that process, the nature of their activities, and the resultant data available to the test planner or test analyst. In addition to those aspects of the program, there are considerations which are more system specific. These considerations are directly related to the specific missile system hardware, its intended operating environment, both the operational and maintenance concepts, and the missile system's projected life cycle profile. A sound understanding and working knowledge of each of these areas will be required to effectively project dormant reliability at an acceptable level of confidence.

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5.2.1 Hardware.

A thorough understanding of the hardware being tested is absolutely essential to the effective conduct of the test. For reliability testing and assessment, it is especially important that the current design be understood. Furthermore, the specific design or configuration of any element of the missile system used in the overall test program must be known. The more detailed knowledge the operational tester possesses about the new missile system, the greater the opportunity to relate it to a similar system, even if the comparison occurs at the subsystem level. The new missile may not be like any existing system, but its subsystems may be similar to those of various other missile systems which could provide usable data for initial analyses and projections.

5.2.2 Environment.

The operational environment to which the missile system is to be subjected can be a critical factor relative to dormant reliability. Failure rates have been shown to vary with stored environment. Since the missile is likely to spend the vast majority of its life in a dormant condition, it will be important to thoroughly understand the environment in which it is dormant. Further, if the missile is to transition between various environments without being functionally operative, the relative time spent in each environment and some understanding of the manner in which the missile reached each environment should be known. Structuring a comprehensive test to effectively account for various environmental factors will require knowledge of those environments. As a minimum, the most critical environments should be accounted for in an attempt to provide some bounding function to the dormant reliability projections.

5.2.3 Concept of Operation.

It can be stated with reasonable assurance that accurate prediction of a missile system's operational reliability without knowledge of its

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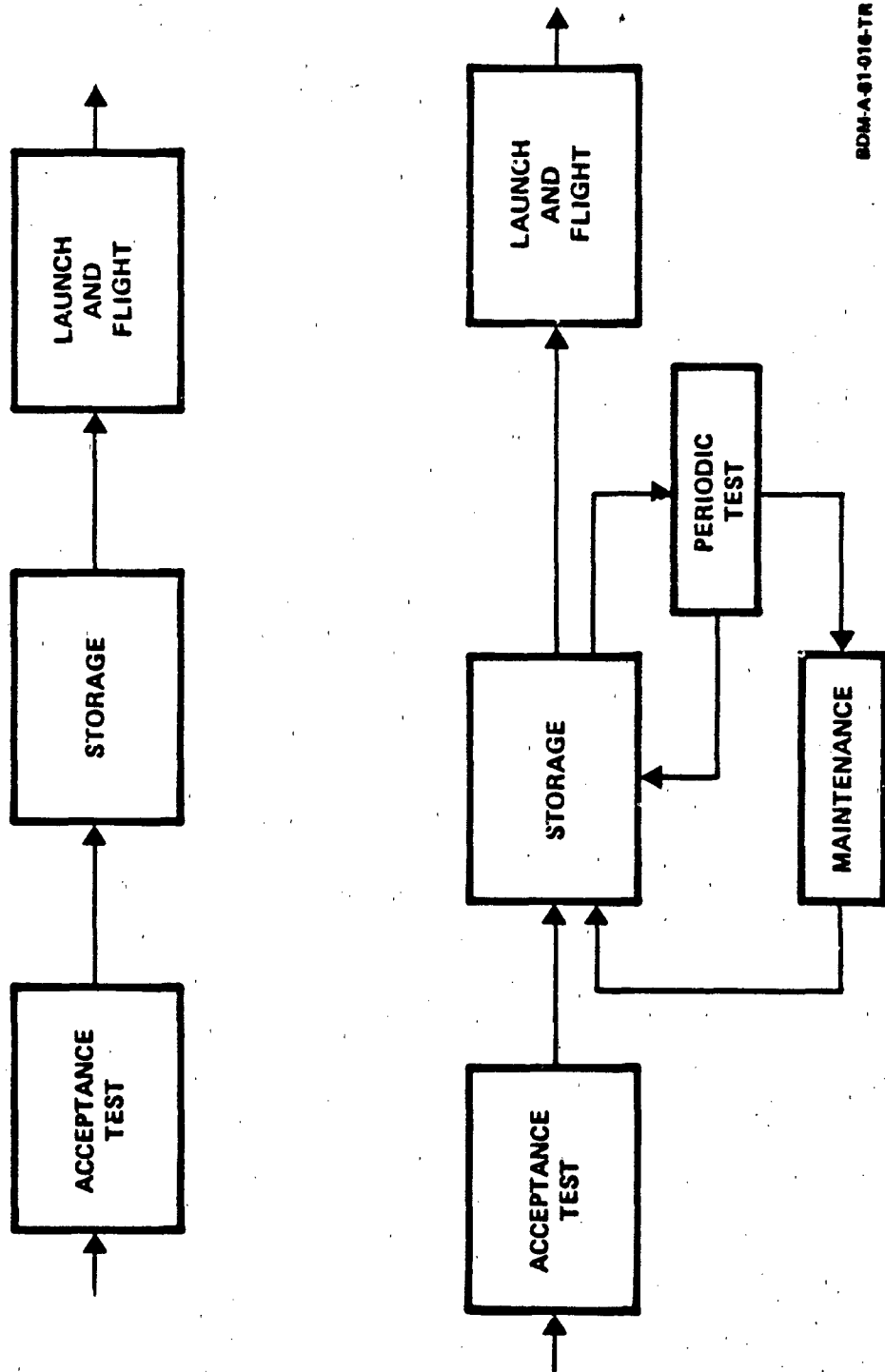
concept of operation is impossible. There can be no doubt that such a statement can be made if the objective is to estimate the missile system's dormant reliability and the relative impact of dormancy on operational reliability. Recall the conceptual definition of dormancy as provided in section III and particularly in figure 2. Determination of actual conditions and periods within the missile system's life cycle which constitute dormancy is a non-trivial exercise. It must be uniquely developed for the missile system under consideration at the subsystem level within the context of the concept of operations.

5.2.4 Maintenance Concept.

The preceding paragraph could probably be repeated here with no loss of impact because the maintenance concept is no less important than the operational concept. They are equal partners in developing the missile system's life cycle profile. As a missile or a missile subsystem cycles through various phases as portrayed in figure 6, the level and frequency of maintenance expected to be performed must be known. For example, will continuous monitoring be employed? Will the missile or major subsystems be subjected to periodic checkout and repair? Will some form of wooden round concept be employed? These questions must be addressed early in the planning phase if an adequate test program is to be developed. If data from similar missile systems or subsystems are to be used during early reliability prediction activities, then it will be necessary to understand the maintenance concept employed within that system.

5.2.5 Life Cycle Profile.

The missile system's life cycle profile provides the cornerstone upon which to build reliability predictions. Figure 6 depicts a simplified representation of two typical missile system life cycle profiles. They very simply characterize two different concepts: no maintenance and



BDM-A-91-016-TR

Figure 6. Typical Missile System Life Cycle Profiles

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periodic maintenance. The life cycle profile for a specific missile system or subsystem will be tailored to that system. It should reflect as accurately as possible the various application and environmental states within which the missile systems will reside, the sequence of transition among states, and the time spent in each state. Obviously, the earlier such a life cycle profile is constructed, the earlier the operational tester will be able to develop reliability predictions, estimate dormant reliability, identify sources of data, provide requirements for system testing, and identify OT&E test sensitive elements.

The level of detail provided in the life cycle profile will depend upon the level of detail required to accurately describe the specific missile system. In general, it will be driven by the operations and maintenance concepts and the degree to which it is desired to isolate failure rate data. For example, assume that captive carry failure data is to be accounted for as a subset of failure data associated with transportation and handling. Then the life cycle profile should reflect transportation of the missile to the aircraft as a distinct item rather than embedding it in the captive carry block.

A life cycle profile tends to tie the system specific considerations and concepts into a picture of how a typical missile exists over a long period of time. A life cycle profile may be represented by state diagrams defining how the missile is planned to be transitioned from one state to another, or by simply defining the various possible states and allocating the proportion of time spent in each state.

It is important to note that a life cycle profile for a missile system at one location or Air Force base may be quite different from a profile for the same missile system at another location or base. Preliminary analysis may only consider a "typical" location with "typical" deployment numbers, etc. Even very similar missile types may have widely divergent life cycle profiles since they may be used extensively for training exercises, or may be stored in different configurations or tested in different ways.

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A good example of the divergence in life cycle profiles between similar missile systems is provided by the ALCM and GLCM systems. The ALCM and the GLCM are nearly identical in terms of missile components and electronics. However, their deployment policies, methods of storage, maintenance, and checkout concepts are quite different. It stands to reason, therefore, that nearly the same missile flight vehicle, in the ALCM and GLCM case, may exhibit quite different day-to-day failure characteristics. A further delineation of the life cycle profile for the ALCM and GLCM may illustrate this in more detail.

5.2.5.1 ALCM.

The proposed operational and maintenance concept requires the ALCM to be stored in an all up round configuration on pylons or launchers for long periods of time. Operational readiness or verification testing will occur on a yearly cycle basis. It can be estimated that an average ALCM can easily spend greater than 95 percent of its life in a dormant state. The dormant reliability, therefore, becomes of great importance in determining the overall readiness state of the ALCM weapon system. The issue of ALCM dormant reliability becomes even more important under the proposed operational concept of transferring ALCMs directly from igloo storage to the aircraft and performing only a minimal go/no-go check before aircraft takeoff, captive carry, and ALCM launch. Most likely, any ALCM failures that occur in storage (and after verification testing) will not be detected before missile launch. Although the life cycle profile of an ALCM indicates that an average ALCM will reside in a dormant state most of its life, it remains in igloo (or deep) storage only for a portion of its non-operational life. ALCMs on pylons or rotary launchers are placed on aircraft standing alert for as long as three-month periods. Thus, an ALCM on a pylon may be exposed to runway temperature and environment variations for long periods. Fully loaded pylons or launchers are also continually being transported between and about igloo storage areas, the integrated maintenance facility (IMF), and the flightline alert areas.

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The major states in which an ALCM will reside can be defined as igloo storage, IMF storage, captive inactive (alert status), ground active (being tested with an electronic system test set), captive active, and free flight. Note that these definitions are in consonance with the ALCM test program and are not in the same terms as the definitions in section III, although they are relatable. Transition between states usually requires a transportation activity. Based upon estimates of how many ALCMs on an average Air Force base are in each state at a random point in time, the amount of time an average ALCM spends in each state may be estimated. For instance, if a base is allocated 192 all up rounds (AURs) that include warheads, and 23 unarmed (spare) ALCMs, the operational and maintenance concepts indicate that at a random point in time there will be an average of 60-72 AURs on flightline alert (captive inactive), about 5 AURs and 2 unarmed ALCMs residing in the IMF, 115-127 AURs in igloo storage, and 21 spare ALCMs in unarmed storage. One or two AURs in the IMF will be under test (ground active) at any random point in time. Since the total population of ALCMs at a base will be regularly cycled through igloo storage, flightline alert, IMF, and unarmed storage, an average ALCM will spend approximately the following percentage of its life in the indicated states:

- a) Igloo storage - 53 to 59 percent
- b) Flightline alert - 28 to 33 percent
- c) IMF inactive - 2 to 3 percent
- d) IMF active - .5 to 1 percent
- e) Unarmed storage - 10 percent
- f) Captive carry (Active) - less than 1 percent
- g) Free flight - much less than 1 percent.

5.2.5.2 GLCM.

The proposed GLCM operational and maintenance concept indicates that the GLCM will be handled quite differently from the ALCM. The GLCM, with associated rocket booster, will be stored as an all up round (AUR) in a

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chemically inert environment inside pressurized canisters. Canisters will be mounted on transporter erector launchers (TELs) and stored in igloos at an Air Force base. Although it is currently unclear whether GLCMs will be powered during an alert cycle, it is possible that a GLCM may never have power applied to it, even for test purposes, after the initial certification check at the base. Thus, the GLCM can be looked upon as much closer to a wooden round than the ALCM. However, since TELs will be moved at regular intervals for TEL maintenance and training, GLCM AURs will be dismounted and mounted somewhat frequently. The current maintenance concept calls for the GLCM AUR to be sent to depot maintenance for overhaul and recertification every three years.

In normal day-to-day peacetime operations, a GLCM will reside totally in an environmentally benign igloo or IMF storage area (the alert area may be considered igloo storage). However, if a failure occurs during storage, only a minimal possibility of detection exists before the three year depot recertification cycle occurs.

When considering the life cycle profiles for both the ALCM and GLCM, the probability of obtaining an operational (non-failed) missile at a specific point in time will most likely be quite different for each missile. Furthermore, that probability will be dependent upon different factors. For the ALCM, the probability is dependent upon factors such as flightline alert environment, probability of failure detection during recertification tests, and stress levels during power on/off situations, among others. For the GLCM, the probability is more a function of the upload/download or transportation stress, inherent aging effects and manufacturing quality control.

5.3 TEST AND EVALUATION CONSIDERATIONS.

An overall concept of dormant reliability testing was introduced in the preceding section. Particular attention was given to techniques employed by the missile system developer early in the missile system's life cycle. This section will focus on that portion of the overall

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system test program which is of principal concern to the operational tester--OT&E. Some particular considerations which are of interest to the operational tester include inherent limitations in the OT&E process, the role of sampling and its relationship to OT&E, methodologies for projecting mature missile system dormant reliability based upon OT&E results, and capabilities for verifying or establishing the validity of early reliability predictions.

5.3.1 Test Limitations.

Major limitations in an OT&E program can generally be classified as resource related. Time and test assets comprise the principal categories. Seldom, if ever, is there sufficient time (from the tester's perspective) to accomplish a thorough and adequate OT&E program. This tends to be a more severe problem for IOT&E than for FOT&E, hence a specific AFTEC concern. If the time available for assessing the operational effectiveness of the missile system is not considered sufficient, there can be no doubt that determining the effects of dormancy from test data will be extremely difficult. It reemphasizes the need for early involvement and identification of resources necessary to accomplish the test program. Even with early participation, there will be limited assets available for the test program, particularly for dormant reliability testing. Both the quantity and the quality of available test articles can limit the effectiveness of the OT&E program. In addition to the limited number of missiles available for testing, those available during IOT&E are generally preproduction models which may exhibit failure modes and rates not representative of the ultimate production version. While these potential problem areas will not likely be eliminated, they may be somewhat mitigated through careful planning and evaluation.

5.3.2 Sampling.

It is not feasible to obtain failure rate measurements on entire populations of missile systems. Therefore, it is understandable that the techniques of reliability measurement rest upon statistical concepts.

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Such techniques permit the extrapolation of results obtained from a sample to the total population and possibly to other similar populations. Whether testing for operating or dormant reliability, it is necessary to determine whether or not the missile system meets specified criteria. Selection of an appropriate sample of missile systems for testing depends upon the hypothesis to be addressed and the potential risks associated with accepting or rejecting the test results. These considerations are discussed in more detail in annex D.

Determination of the test sample size also depends upon the test method to be employed. Two commonly used methods for dormant reliability testing are fixed-length tests and tests truncated after a specified number of failures. Within each method, testing can be accomplished either with or without replacement. Under a replacement concept, failed test items are either replaced with new ones or they are repaired and returned to the sample for further testing. Within a fixed time test, testing with replacement is most commonly used; it generally requires fewer samples.

5.3.3 Projection Methodologies.

It has been pointed out that the issue of dormant reliability is part of a substantially larger problem--projecting mature missile system reliability early in the missile system's life cycle. There are two aspects to the projection problem, although the difference, while real may be very subtle. There must be an initial estimate of system reliability while subsequent projections tend to be refinements of previous projections. Several projection methodologies are available (see Projections of Suitability OT&E Results to Mature System Operations, BDM/A-81-052-TR) depending on the missile system development phase.

During the planning phase, methodologies will generally be restricted to those which can use non-measurement or limited part test data. Contractor predictions, judgement, comparability analyses, and simulation/modeling will provide the primary tools. During IOT&E, as test results

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become available, regression, Gompertz, and surveillance and inspection methods can be added. These varied methodologies, with the exception of contractor predictions, will still be applicable during FOT&E.

5.3.4 Validation and Verification.

Validation and verification of reliability projections is a difficult and often time consuming task. By its very nature, "proving" estimates of dormant reliability is non-trivial. Field results will quite often require 5 to 10 years of exhaustive measurement, data collection, and analysis before dormant reliability predictions can be verified. Since the verification process provides the empirical feedback necessary to help validate the reliability projection methodology, the validation process is also accomplished over an extended period of time. Experience, of course, can be an integral factor for both validation and verification. Data from similar systems can be used in the process provided that the analyst correctly assesses the applicability of that data.

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SECTION VI TOOLS AND TECHNIQUES FOR POTENTIAL AFTEC APPLICATION

6.1 AVAILABILITY AND APPLICABILITY.

It is clear from previous sections that tools and techniques for estimating, predicting, projecting, or assessing dormant reliability during OT&E are limited in terms of both their availability for use and their direct applicability in terms of the inherent limitations and bias associated with differing goals in the development process. The only logical course to pursue, then, is to take the best that is available, modifying where possible, or to suggest new methods which could be pursued in the future.

6.2 INITIAL ESTIMATES.

6.2.1 MIL-HDBK-217C.

MIL-HDBK-217C contains the most widely used methods for initial estimates of reliability. As discussed earlier, it applies mainly to electronic components at the piece part level. There are, however, some considerations which may render this approach useful for projection purposes.

First of all, the MIL-HDBK-217C methods result in an inherent dormant reliability prediction which is generally not applicable to field conditions (because of type 2 and type 6 failures). However, as in the discussion of the definition of dormancy, the operationally ready storage subset may actually represent this inherent failure rate condition, depending on the level of maintenance and test/checkout. In these cases, the contractor prediction could be used directly. If significant maintenance exists, then the contractor prediction should be adjusted type 2 and 6 failures. An initial, approximate "rule of thumb" for this condition is that total failures are approximately twice the inherent or type 1 failures.

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A second and very important consideration is that dormant reliability should be addressed at the subsystem level. When one realizes that a complete (typical) tactical missile can be represented by less than 50 part types, it becomes fairly obvious that "building up" a particular subsystem from parts would not be particularly difficult or time consuming. If a subsystem parts list could be obtained from the SPO/development contractor, an AFTEC analyst could perform the necessary MIL-HDBK-217C operations within a day. Although AFTEC has generally not been involved at the piece parts level, in some situations it might be well worth considering. This is particularly true in missile systems since the number of major subsystems range from about 6 for an air-to-air missile to about 13 for a cruise missile, with only a few of these being electronic in nature.

6.2.2 Piece Parts for Non-Electronics.

Part reliabilities and piece part methodologies for other than electronic devices are available in RADC and Army Missile Command handbooks. The "parts" tend to be aggregated at higher levels than those of the MIL-HDBK-217C listings (e.g., generators, pumps, actuators, regulators, rocket engines, valves). Thus, a buildup approach is further simplified. The drawbacks to these documents are that they have not received "MIL STD" status, as such, and are slightly harder to procure. They are, however, in current common usage.

6.2.3 Piece Part Surrogates.

If very quick estimates are necessary, there are several estimating relationships which have been used in the past. These estimating relationships essentially provide a surrogate for an aggregated parts level. Surrogate measures include such things as complexity, volume, weight, function, and cost. Simple or weighted averages could also be substituted

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for an actual parts count. Surrogate methods provide only a gross estimation of reliability and are generally used for very quick trade-off analyses by system developers. Documentation on these methods is virtually non-existent for obvious reasons.

6.2.4 Piece Part Computer Codes.

Almost every organization involved with piece part methodologies will generally have a simple computer code or "model" which does the "look-up" and computations involved. In late 1975 and 1976, AFTEC/OAO investigated one such code called "Predictor." The original code was developed by R/M Systems, Inc. under subcontract to The BDM Corporation for AFTEC. Preliminary investigation indicated that the use of this code to "look-up" and accumulate part failure rates and the associated maintenance man-hours could produce manpower predictions in the range of within 10 percent of other methods. In addition, some surrogate methods were included for aggregating "the parts" at subsystem level. Because the weapons systems under consideration at that time could be "measured," and only operating systems were being tested, the development effort associated with such a code was not really necessary. For this and a variety of other reasons the pursuit of such a methodology was gradually dropped.

The point to be made here is that dormant reliability estimates (given that "measurement" is difficult) could be enhanced by a similar type of code using existing dormant data bases with refinement over time. More consideration on the relative value of such a development or collaboration with other agencies toward a similar end is warranted.

6.2.5 Comparability Analysis.

Comparability analysis is a recognized technique that has been used with success in the past by AFTEC. There are, however, some constraints. The data base used, the skill of the person making the comparability decisions, various adjustments that must be made when 100 percent

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comparable data do not exist (the general and most frequent case), and the ingenuity of the analyst applying the results are all limiting factors. Even with these caveats, however, comparability analysis is probably the single best technique that can be used when firm reliability values based on actual system experience and data are not available.

This approach requires detailed knowledge of the specific missile system under consideration as well as all other systems/subsystems which may be similar. One advantage in performing comparability analysis on a missile system is that similarities are often the rule rather than the exception, especially within a missile series. Figure 7 provides an example of a top-level comparison of the AIM-9 series. Even outside of a series, the chances are good that some subsystems will have directly comparable counterparts in other missile systems, aircraft, RPVs, etc. because the technology just does not change that fast.

Given that comparable or similar subsystems exist, the problem then becomes one of homing in on dormant reliability by subsystem. If data on dormancy for the similar systems do not exist, one is left with factoring operating failures to dormant failures, and this process is generally not very accurate (see paragraph 6.2.6). The need to collaborate with other agencies who maintain dormant data bases thus becomes patently obvious.

6.2.6 K Factors.

A K factor is an adjustment from one condition or set of conditions to other conditions. In the general sense, the term adjustment factor is more appropriate, but the use of the designator "K" has become common to reliability engineering and reliability handbooks.

It is impossible to generalize the applicability or validity of adjustment factors. First of all, the number, type, and application of adjustment factors is almost limitless. Secondly, the validity depends upon the application itself. The use of adjustment factors tends to be more art than science and is therefore strongly influenced by the skill,

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	AIM-9B	AIM-9B with PGW Mod. 2	AIM-9C	AIM-9D	AIM-9E	AIM-9F	AIM-9H	AIM-9J	AIM-9L
Guidance and control section (GS): Seeker head		development of AIM-9B seeker head with	development of AIM-9B seeker head with	development of AIM-9B seeker head with	seeker head similar to AIM-9D, but with:	seeker head similar to AIM-9G, but with:	seeker head similar to AIM-9E, but with:	development of AIM-9H seeker head with	
- Detector and cooling system	uncooled PbS detector	- CO ₂ cooled PbS detector - coolant tank (85 cm ³) in GS - cooling period 2.5 h at +20 °C	- R ₂ cooled PbS detector - coolant tank (8 l) in launcher - cooling period 2.5 h	- thermo- electrically cooled PbS detector - Peltier cooler in GS				- Argon cooled InSb detector - coolant tank in GS	
- General data		- higher seeker sensitivity - improved back- ground suppression - dead zone around sun 5° - semiconductor electronics - Si dome - 25° look angle - rotating reticle (70 Hz) - unobstructed mechanism - 4° field of view - 11°/sec track- ing speed - dead zone around sun 20° - 63 mm dome radius - glass dome	- higher sensi- tivity - higher reac- tive (125 Hz) - greater look angle - smaller field of view (25°) - slightly higher tracking speed (12°/sec) - smaller dome diameter - MgF ₂ dome	- higher reac- tive (100 Hz) - greater look angle - smaller field of view - increased tracking speed (16.5°/sec) - MgF ₂ dome	- increased tar- get acquisition capability (SEAM)	- solid state electronics - increased tracking speed	- partly solid state elec- tronics	- fixed reac- tive - AM/FM modula- tion - tried secondary mirror	
Control servo unit	with simple non- detachable delta control surfaces	as AIM-9B	modified AIM-9B servo unit with: - higher actuating moment (140 Nm) - longer burning gas generator - detachable control surfaces	modified AIM-9B servo unit with: - improved cooling - detachable control sur- faces	as AIM-9D	servo unit similar to AIM-9G but with: - higher actua- tion moment (120 Nm) - thermal battery	improved AIM-9B ser- vo unit with: - higher actua- tion moment (125 Nm) - detachable double-delta control sur- faces - longer burning gas generator	modified AIM-9H servo unit, but with: - detachable double-delta control surfaces	
Warhead (WW)	Fragmentation warhead	as AIM-9B			as AIM-9D	as AIM-9D	as AIM-9D	as AIM-9B	
Proximity fuse (PF)	passive IR proximity fuse	as AIM-9B		optional IR or HF proximity fuse	slightly modified as AIM-9D AIM-9B proximity fuse	as AIM-9D	as AIM-9D	as AIM-9E	active IR proximity fuse
Motor (M)	solid fuel motor with - 30,300 Nsec total impulse - 2.2 sec burn time	as AIM-9B		improved motor with - greater total impulse - longer burn time	as AIM-9B	as AIM-9D	as AIM-9D	as AIM-9B	as AIM-9D possibly improved
Positioning of main com- ponents	GS/WW/PF/M	as AIM-9B		GS/PF/WW/M	as AIM-9B	as AIM-9D	as AIM-9D	as AIM-9B	as AIM-9D
Missile duration, sec	20	as AIM-9B		60	as AIM-9B	60	60	40	60
Missile launch weight, kg	70.6	75.0		85.0	74.5	87.0	86.0	75.0	as AIM-9H
Missile length, mm	2,820	2,800		2,870	3,000	as AIM-9D	as AIM-9D	3,070	2,800
Wing span, mm	500	as AIM-9B		530	as AIM-9B	as AIM-9D	as AIM-9D	as AIM-9B	as AIM-9D

BDM-A-01-016-TR

Figure 7. Comparison of the Various Sidewinder Types with the AIM-9 B Sidewinder IA (taken from International Defense Review, Special Series 10, 1980, without modification)

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expertise, experience, and ingenuity of the person using them. Indiscriminant or uninformed use of adjustment factors is certainly less than prudent. In many cases, adjustment factors have been backfitted to data sets or applied to "get the right answer" or meet specification. This practice has obviously done nothing to enhance the acceptance of adjustment factors as a valid analytical tool.

The fact is that adjustment factors have been employed to accurately replicate reality and to project or predict future states. Comparability analysis, for instance, almost always includes some sort of adjustment, even if it is judgmentally derived. In some cases (as in early estimates of dormant reliability), adjustment factors are the only possible alternative, but extreme care should be exercised in using them.

The adjustment factors in reliability handbooks are fairly good if the user has an understanding of the application and meaning of the results, and if used they are within the strict confines of the methodologies. MIL-HDBK-217C, for instance, gives the following caveat in bold type:

CAUTION

THE FAILURE RATES PRESENTED APPLY TO EQUIPMENT UNDER NORMAL OPERATING CONDITIONS, i.e., WITH POWER ON AND PERFORMING ITS INTENDED FUNCTIONS IN ITS INTENDED ENVIRONMENT. EXTRAPOLATION OF ANY OF THE BASE FAILURE RATE MODELS BEYOND THE TABULATED VALUES, SUCH AS HIGH OR SUB-ZERO TEMPERATURE, OR ELECTRICAL STRESS VALUES ABOVE 1.0 OR AT 0 OR EXTRAPOLATION OF ANY ASSOCIATED MODIFIERS IS COMPLETELY INVALID.

While adherence to this caution is recommended, the latest update of MIL-HDBK-217C contains as part of its documentation an environmental factors survey which shows some promise for application at above the piece part level. A delphi technique was employed to survey experts in

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the reliability field who were asked to establish an order of significance for factors in various use environments. In addition, the expertise of each respondent was also rated and limited field data were included where possible. The results of this survey are provided in figure 8. The manner in which the survey was conducted and its apparent generality give some credence to the possible use of these factors as adjustments at the subsystem level. Please note that the nonoperating environment listed in figure 8 follows the definition given in the update to MIL-HDBK-217C; it is not necessarily the same as dormant as defined in this report. It is, in fact, closer to operationally ready storage (with no operating/test equipment stress applied) or inherent dormant reliability. If the inherent dormant reliability of a missile, by subsystem, can be measured or predicted, then these environmental factors could be used to adjust this value to those for different dormancy states (transportation, launcher carriage, captive carry, etc.) as a "ball park" estimate.

Another adjustment factor worthy of some discussion is laboratory (a contractor estimated) reliability to field reliability. AFTEC has successfully used this adjustment in LCOM simulations of aircraft systems. This success, however, is strongly related to knowledge and experience with aircraft systems in general, and good historical data for comparability analysis in particular. Adjusting for type 2 and type 6 failures is possible for dormant missile systems, especially when comparable field data are available or if the development contractor's "censoring" of non-relevant failures can be closely monitored and tracked. Gross-level extrapolations from laboratory to field reliability without some insight is risky at best.

Several studies available in current literature attempt to adjust from operating to non-operating conditions. This particular adjustment appears to have very limited potential application unless accomplished (with great caution) at the piece part level. Results vary widely and there appears to be no universal application. Use of a system- or subsystem-level adjustment for operating to non-operating failure rates should be used only as a last resort, at least until much more research has been accomplished.

ENVIRONMENTAL SEVERITY RATIO	ENVIRONMENT	INFLUENCE FACTORS														TEMPERATURE-ALTITUDE	SOLAR RADIATION	PYROTECHNIC SHOCK (HIGH FREQUENCY)	LOADS SHOCK	FUNGUS/MICROBES	SALT FOG	HUMIDITY	EXPLOSIVE ATMOSPHERE	LEAKAGE (IMPERSON)	ACCELERATION	RANDOM VIBRATION	SINE VIBRATION	ACOUSTICAL NOISE	PRESSURE SHOCK	SPACE SIMULATION	TEMPERATURE-HUMIDITY- ALTITUDE	ELECTROMAGNETIC ENVIRONMENT - EME
		PAK	ALTITUDE	DUST/SAND	LOW TEMPERATURE	TEMPERATURE SHOCK/CYCLING	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE	TEMPERATURE-ALTITUDE
1	GROUND, BENIGN	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1	1.5	1
2.7	GROUND, FIXED	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
3.5	GROUND, MOBILE, WHEELED	5.3	5.42	5.89	5.3	5.42	5.89	5.3	5.42	5.89	5.3	5.42	5.89	5.3	5.42	5.89	5.3	5.42	5.89	5.3	5.42	5.89	5.3	5.42	5.89	5.3	5.42	5.89	5.3	5.42	5.89	5.3
11.5	GROUND, MOBILE, TRACKED	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
12.5	MANPACK	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61	5.61
7.3	NAVAL, SHELTERED	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
16.8	NAVAL, UNSHELTERED	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52	5.52
20.6	NAVAL, UNDERSEA, UNSHELTERED	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
6.0	NAVAL, BENIGN, SUBMARINE	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19.2	NAVAL, HYDROFOIL	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
10.2	AIRBORNE, INHABITED, TRANSPORT	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
19.5	AIRBORNE, INHABITED, FIGHTER	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
23.1	AIRBORNE, UNINHABITED, TRANSPORT	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
33.5	AIRBORNE, UNINHABITED, FIGHTER	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
27.6	AIRBORNE, POSTARY WING	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
42.7	MISSILE, LAUNCH/REENTRY	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38	6.38
287.9	TACTICAL MISSILE, LAUNCH	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
722.6	CANNON, LAUNCH	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
37.1	UNDERSEA, LAUNCH	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44	3.44
12.6	MISSILE, FREE FLIGHT	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
17.6	AIRBORNE, MISSILE, FLIGHT	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85	5.85
2.1	SPACE, FLIGHT	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
1.1	NONFLIGHT	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1

NOTE: THE NUMBERS INSIDE THE MATRIX REPRESENT THE IMPORTANCE OF EACH FACTOR USING A SCALE OF 1 TO 10 WITH 10 BEING THE HIGHEST SEVERITY LEVEL.

BDM-A-81016-TR

Figure 8. Environmental Severity Ratios and Influence Matrix

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At a more detailed level, failure modes and effects analysis could be used to advantage. Where the non-operating failure modes are the same as the operating failure modes, adjustments might be possible based on stress ratios or similar estimating relationships. It might also be possible to correlate how malfunctioned codes from comparable data to failure modes. (More investigation is necessary here.) Where operating failure modes are very different from non-operating failure modes--as is the case for turbine engines--then no direct adjustment or factoring should be attempted.

6.2.7 Other Estimating Techniques.

There are several additional estimating techniques which have potential for AFTEC application to the dormancy problem, but for the most part they are not proven and should be viewed only as possibilities. These techniques are based on adaptation or extrapolation of contractor screening and testing. Each technique is discussed relative to the appropriate contractor activity.

6.2.7.1 Estimates from Acceptance Testing.

In the ideal sense, acceptance testing should eliminate all defective missiles/missile subsystems prior to delivery to the customer. In a pragmatic sense however, this is rarely 100 percent true and close examination of the testing methods and equipment should be accomplished. An estimate from the development contractor regarding the test efficiency or type 1 error (probability of accepting a defective item) should be requested as early as possible. Expert judgment and comparable experience can also be used to back up the contractor's estimate. This estimate is vital (even if there is no clear-cut way of arriving at a figure) because it is used to predict undetected failures entering the field environment.

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6.2.7.2 Estimates from Accelerated Stress Testing.

If accelerated stress tests are conducted at different stress levels and sufficient stress tests are conducted to compute an MTBF at each stress level, then regression techniques can be employed to estimate inherent dormant reliability by extrapolating backwards to zero stress and computing the corresponding MTBF. A hypothetical example is provided in figure 9.

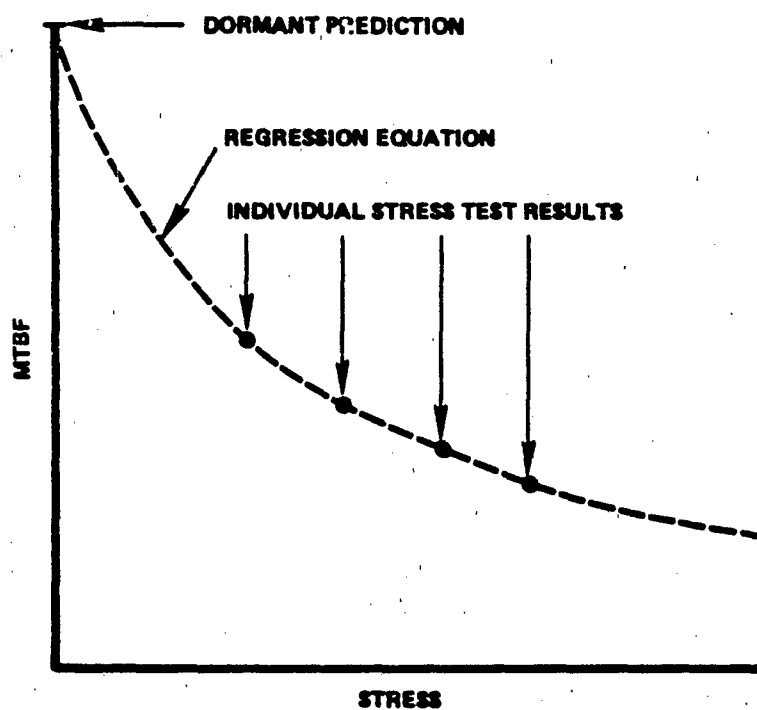
If this methodology is to be employed, AFTEC involvement early in the development process is essential to ensure that sufficient tests are accomplished at varying stress levels.

In addition to a prediction of inherent dormant reliability (zero stress), it may also be possible to directly correlate stress tests at low power levels to the dormant reliability expected at those same stress levels, i.e., guidance systems in ICBMs maintained at X percent stress continuously, or the stress level induced by test equipment (if less than fully operating).

6.2.7.3 Estimates from Accelerated Temperature Cycling.

It is generally accepted that accelerating temperature cycles can be used to replicate the aging process. Some doubt does remain, however, as to the relative contribution of seasonal temperature variation versus actual aging (additional research is indicated). Given that the concept holds, accelerated temperature cycling, if conducted at the subsystem level, could be used directly as an estimate of inherent dormant reliability by factoring the failure rate observed during tests by the age acceleration ratio. The validity of the ratio between the accelerated time and real time is the critical issue. This method has been used by the Naval Ordnance Station at Indian Head, Maryland on rocket motors. It should be equally applicable to warheads and other systems where age related failure modes are indicated.

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BDM-A-61-016-TR

Figure 9. Hypothetical Inherent Dormant Reliability Predicted by Regression Analysis

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6.2.7.4 Shelf Life Estimates.

Subsystems such as solid rocket motors and warheads exhibit dormant reliability characteristics which are analogous to shelf life in that they are generally perishable and cannot be repaired or returned to their original specifications. In addition, these systems do not experience intermittent or periodic operation. Thus aging, which is the predominant factor in shelf life, applies. The actual rate of chemical decomposition can be computed for explosives and propellants. However, these subsystems tend to have very long dormant lives. Hence the contractor's estimate of shelf life or comparability data from the Naval Ordnance Station at Indian Head, Maryland should be sufficient as an estimate of dormant reliability. Another necessary consideration is that packaging influences shelf life. If the protection from the environment is different than that afforded by the packaging associated with shelf life predictions, then an adjustment based on environmental severity (i.e., humidity, temperature, salt, fog, etc.) should be considered.

6.2.7.5 Estimates from Vibration Testing.

The development contractor will normally perform various types of vibration testing as a screen. With careful consideration of the vibration test itself and actual conduct of the test under the proper conditions, it might be possible to derive factors for the various modes of dormancy where vibration is experienced such as transportation and handling, launcher carriage, and captive carry. Major problems, however, could be anticipated in that to properly use this test as a predictor for dormancy, the test should be conducted with "power off." Actual measurement of when failures occurred is then impossible. Proper sample size selection and a relatively large number of tests at various fixed lengths of time could be used to statistically determine failure rates from vibration testing.

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6.2.7.6 Estimates from Power on/Power off Cycling.

The use of power on/off cycling has been used in several studies to predict dormant reliability (see reference 18). Results vary widely and its applicability appears to be relevant only at the piece part level. The comments regarding adjustment factors for operating to nonoperating also apply.

One aspect of power on/off cycling is extremely useful. Dormant systems may experience various power-on cycles due to test equipment or maintenance and other aspects of the concept of operations. This periodic turn on/off will influence dormant reliability in a synergistic manner as previously discussed. The failure rate from power on/off cycling should be applied to the system's life cycle profile in terms of on/off cycles to failure every time the system is tested or otherwise "turned on." This will assist in capturing all of the synergistic relationships inherent in the dormancy problem.

Another very practical use (in an estimating sense) is that it could be used directly as a surrogate for the failures induced by test equipment or maintenance by equating the number of such events to the number of power on/off cycles.

6.2.8 Initial Estimating Techniques - Overview.

The techniques for initial estimates of dormant reliability are primarily aimed at predicting inherent dormant reliability except as noted in previous paragraphs and in table 1 which follows. Inherent dormant reliability (by estimation and test) is the central and most critical building block of the overall assessment approach which is outlined in section VIII. Table 1 provides a brief mnemonic for each estimating technique, the form of the resulting estimate, and an assessment of the utility to AFTEC, estimated in terms of soundness, useability, and accuracy of the approach.

Table 1.

Overview of Estimating Techniques

<u>ESTIMATING TECHNIQUE</u>	<u>FORM OF RESULT</u>	<u>UTILITY</u>
1. MIL-HDBK-217C	Inherent dormant reliability for electronic systems/subsystems	Good, within confines of, HDBK, must be built up from piece part level
2. RADC and Army Missile CMD HDBKs	Inherent dormant reliability for electronic/non electronic systems/subsystems	Same as 1
3. Piece Part Surrogates	Inherent dormant reliability by subsystem	Poor to fair
4. Piece Part Computer Codes	Inherent dormant reliability by subsystem	Good potential given development effort
5. Comparability Analysis (Dormant to Dormant)	Inherent or overall dormant reliability by subsystem depending on data structure	Excellent with very experienced person, good for others
6. Comparability Analysis (Operating to Dormant)	Inherent dormant reliability by subsystem	Poor to fair, must use generally unreliable K factors
7. Adjustment (K) Factors	See breakout below	See breakout below
a. HDBKs	Adjustments for learning, stress, environment, etc. in piece parts methods	Fair to good, must be used within the confines of the HDBKs

Table 1.

Overview of Estimating Techniques
(Continued)

<u>ESTIMATING TECHNIQUE</u>	<u>FORM OF RESULT</u>	<u>UTILITY</u>
b. Environmental Severity Ratios	Subsystem level adjustments to inherent dormant reliability resulting in dormant reliability by subsystem by dormant state	Fair to good, excellent potential with more research
c. Lab-Field overall	System/subsystem field dormant reliability - generally represents non-operating states	Very poor (avoid)
d. Type 2 & 6 maintenance	Adjusts "laboratory" inherent dormant reliability to operationally ready storage reliability	Good if used in conjunction with 5, otherwise poor to fair
e. Operating to non-operating (system level)	Adjusts from operating reliability to inherent dormant reliability	Poor
f. Operating to non-operating (subsystem level)	Same as e	Poor
g. Operating to non-operating (part level)	Same as e	Fair to good
h. Operating to non-operating (subsystem level supported by FMEA)	Same as e	Good potential with major development effort

Table 1.

Overview of Estimating Techniques
(Concluded)

<u>ESTIMATING TECHNIQUE</u>	<u>FORM OF RESULT</u>	<u>UTILITY</u>
1. Others	Numerous results	Generally poor to fair
8. Acceptance Test (α_1)	Number of undetected failures	Good but methodology needs refinement
9. Regression analysis on accelerated STRESS TEST data	Inherent dormant reliability	Good potential
10. Accelerated temperature cycling, direct estimate	Inherent dormant reliability	Fair, good potential with additional research
11. Shelf life estimates	Inherent dormant reliability for explosives and propellants by subsystem	Good to excellent
12. Power on/Power off accelerated testing	See breakout below	See breakout below
a. Direct estimate	Inherent dormant reliability	Very poor to poor
b. Number of cycles to failure	Synergistic effects	Fair to good
c. Number of cycles to failure	Induced failures from maintenance and test equipment	Fair to good
13. Vibration testing	Dormant reliability in transportation, launcher carriage or captive carry states	Fair to good

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6.3 PROJECTIONS TO MATURITY.

Projection methodologies are addressed in paragraph 5.3.3 and in detail in Projections of Suitability OT&E Results to Mature System Operations, BDM/A-81-052-TR. The projection methodologies in the above reference are generally applicable to dormant reliability as long as the nature of dormancy is carefully considered as part of the process.

In the ideal case, inherent dormant reliability, operationally ready storage reliability, and dormant reliability by state (transport, captive carry, etc.) should be closely monitored from the first estimates and specifications forward to essentially plot a "bathtub curve." The nature of dormancy and the missile system development process are such that one would expect to see reliability changes appear in "spurts" or by lot. Thus reliability growth curves should look more like step functions than smooth curves.

Another aspect of the nature of dormancy which is critical in this regard involves the definition itself. Refer to section III; note that the definition of dormant, in part, requires an AUR and allows only on-equipment maintenance. Thus, parts and even subsystems in storage and off-equipment maintenance have been excluded from the "aging" process. Although there were very good reasons for doing this, it is important to consider its impact on projections to maturity. As missiles mature and begin to require maintenance for dormant failures, it is likely (depending on the sparing policy) that "old" parts are used. These parts could then also be experiencing age related failures. One might then begin to see an artificially early wear out of the system by repairing with parts that are more likely to fail due to their own age.

6.4 TESTING FOR DORMANT RELIABILITY.

The nature of the dormancy problem, as discussed in section II, is such that traditional test means and methodologies often do not apply. There are a few types of tests, however, that can be conducted by the

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development contractor and by AFTEC during OT&E. Appropriate testing methods and specific experience for those methods were addressed in paragraphs 4.1 and 4.2. Those listed in the state of the art/experience plus others which are deemed appropriate are included in this section. An overview of the general types of tests that can be conducted is provided in figure 10.

Given that only certain types of tests are appropriate in a general sense, it is necessary to further subdivide these possibilities by subsystem type. Certain types of subsystems (rocket motors versus guidance units, for instance) are amenable to only certain types of tests. A discussion of this subject is provided in paragraph 6.4.1.

Finally, from the OT&E perspective, it is necessary to determine which tests should be conducted by the development contractor and monitored by AFTEC and which tests should be conducted by AFTEC during OT&E. These decisions must be keyed to a specific missile life cycle profile. A discussion of this subject is provided in paragraphs 6.4.2 and 6.4.3.

6.4.1 Testing Considerations by Missile Subsystem.

Individual missile subsystems by their very nature are not amenable to all tests. For instance, power on/power off tests on rocket motors and warheads is obviously not appropriate, whereas it is appropriate for guidance units. Table 2 provides a summary of the generic test types that are most appropriate for missile systems, broken out by four subsystem types. Note that the missile system types are generic, and the typical subsystems are generalized examples. A very brief discussion by subsystem follows.

6.4.1.1 Propulsion Subsystem.

The propulsion subsystem of missiles can be either a solid or liquid fuel system. If the subsystem is a solid rocket motor, accelerated environmental testing can be accomplished at the contractor's facility.

SCREENING TESTS (See Annex E)

Acceptance Tests

Accelerated Tests

Power On/Power Off

Test Equipment/BIT On/Off

Environmental

Stress

Test Equipment/BIT Continuous

Transportation and Handling (Increased Frequency)

Launcher Carriage (Increased Frequency)

Mobility Tests

REAL TIME TESTS

Surveillance Tests

Missile System (Storage) Surveillance

Subsystem (Storage) Surveillance

Shelf Life Surveillance

Transportation and Handling (Procedure Oriented)

Mobility Exercises

Captive Carry

Live Firing

BDM-A-81-016-TR

Figure 10. Overview of Dormant Reliability Related Tests

Table 2.
Testing Considerations by Missile Subsystem

SUBSYSTEM	MISSILE				SUGGESTED TEST
	AIR-TO-AIR	AIR-TO-GROUND	CRUISE	ICBM/MRCBM	
PROPULSION	SOLID ROCKET	SOLID ROCKET	LIQUID FUEL TURBINE	SOLID ROCKET LIQUID FUEL	SURVEILLANCE, ACCELERATED ENVIRONMENT SURVEILLANCE, ACCELERATED ENVIRONMENT
CONTROL	ELECTRO-MECHANICAL HYDRAULIC/PNEUMATIC	ELECTRO-MECHANICAL HYDRAULIC/PNEUMATIC	ELECTRO-MECHANICAL PNEUMATIC	HYDRAULIC	SURVEILLANCE, ACCELERATED POWER ON/OFF AND ENVIRONMENT SURVEILLANCE, ACCELERATED ENVIRONMENT
NAVIGATION/ GUIDANCE	ELECTRO/OPTICAL ELECTRICAL MECHANICAL	ELECTRO/OPTICAL ELECTRICAL MECHANICAL	ELECTRICAL		POWER ON/OFF, ACCELERATED ELECTRICAL AND ENVIRONMENT, SURVEILLANCE POWER ON/OFF, ACCELERATED ELECTRONIC, SURVEILLANCE SURVEILLANCE, ACCELERATED ENVIRONMENT POWER ON-OFF, ACCELERATED ELECTRICAL ACCELERATED ENVIRONMENT, SURVEILLANCE
AIR FRAME	MECHANICAL	MECHANICAL	MECHANICAL	ELECTRO-MECHANICAL MECHANICAL	SURVEILLANCE, ACCELERATED ENVIRONMENT

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The Naval Ordnance Station can also be used if the facility is large enough to accommodate the motor. The length of time for the accelerated testing will depend on the time necessary to simulate the proposed storage environment. Surveillance testing can also be used to test for dormant reliability. However, the time to accomplish the real-time surveillance may be quite long, depending on the sample size available. Shelf life surveillance by another agency may be appropriate in this case.

Liquid fuel propulsion systems can also be tested through accelerated environmental testing if the failure mode of the fuel itself does not change. Given early AFTEC involvement, surveillance testing may be a better method than accelerated environmental testing.

6.4.1.2 Control Subsystem.

The control subsystem of missiles is composed of both electro-mechanical and hydraulic (or pneumatic) components. The movement of the control surfaces is accomplished hydraulically by electrical impulses activating the hydraulic motor. Some missiles may use only electro-mechanical components to activate a control surface. The electrical impulse from the guidance unit will activate an electrical motor to move the control surfaces.

The electromechanical systems can use power on/off and environmental cycling in an accelerated manner for testing. The testing of hydraulic systems is more amenable to surveillance and accelerated environment testing, as operation of the system during testing may change the failure mode. Surveillance testing applies in either case.

6.4.1.3 Navigation/Guidance Considerations.

Systems with inertial navigation/guidance are generally more subject to mechanical and hydraulic degradation during storage than are terminally guided (electro-optical) systems. Long term surveillance testing may be more appropriate for inertially guided systems, whereas accelerated

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testing may be more appropriate for terminally guided systems. In some cases, terminally guided systems may simply be mechanically guided, requiring the alignment of the launch platform (aircraft) and free flight to target. In that case, little or no testing would be required.

6.4.1.4 Airframe Considerations.

The assessment of the dormant reliability of different airframes should consider the composition of materials and the complexity of assembly. If the exterior coating of the missile is critical to survivability issues (radar signatures), accelerated environmental testing should be considered to determine corrosion or flaking impacts. Surveillance testing is appropriate in all cases.

6.4.2 OT&E Testing Perspective.

In dormant missile systems, it is critically important that AFTEC pursue early involvement and collaboration in the development/acquisition process since operational testing for dormant reliability is inherently limited. ALL of the weapon system developer's activities as discussed in sections II and V should be closely monitored, particularly those which will ultimately be used for dormant reliability estimating purposes. In addition, particular attention should be given to surveillance tests (structured via early involvement), service reporting/ECPs, engineering "fixes," and development of operational and maintenance concepts.

With this as background, the real issue becomes: which tests are appropriate and necessary for AFTEC to conduct during OT&E. The process involved in this decision is based on a straightforward and logical progression. First, early detailed knowledge of the system itself is necessary. Second, a review of the maintenance and operations concepts should be performed. If these concepts are not available, early collaboration with the development/user community will help in providing at least provisional concepts. From these concepts, a life cycle profile should be constructed, keying on the definitions provided in section III.

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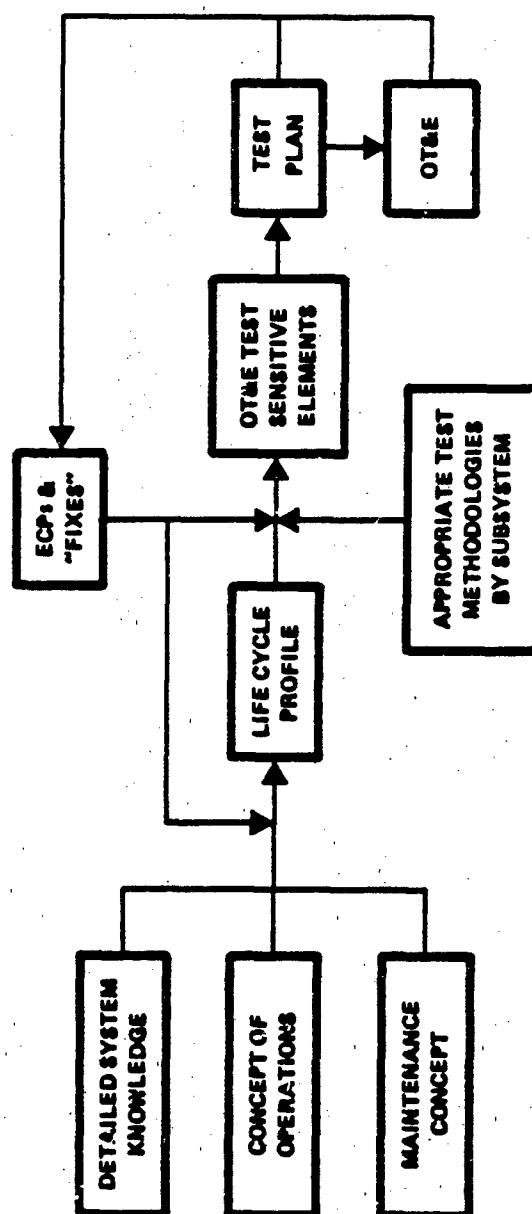
Based on the life cycle profile, decisions can be made regarding the states of dormancy which are sensitive to OT&E and appropriate tests by system/subsystem. In addition, close monitoring of ECPs and engineering "fixes" should provide an input into the decision making process. If these ECPs/"fixes" are significant and are test sensitive, then they should be included where appropriate as updates (realizing that their status is constantly changing). A schematic of the decision making process is provided in figure 11.

6.4.3 Test Sensitive Elements.

The OT&E test sensitive decision process was applied to a typical example in order to verify the logic involved and to examine the test sensitive elements which were thus produced. The concept of operations was that of a typical tactical air-to-air missile. The maintenance concept was periodic test and repair. The life cycle profile used is contained in annex C. A summary of test sensitive elements is provided in figure 12. Specific test sensitive considerations follow.

6.4.3.1 Initial Undetected Failures.

If OT&E is to represent the actual field environment, then test articles (missiles) should be acceptance tested by the contractor and shipped to the field (OT&E test location) as would be the case in actual practice. The undetected failures (α_1) present after acceptance testing and shipping is partially test sensitive. If complete checkout were accomplished when missiles were received (predeployment checkout), some of these previously undetected failures could be found (allowing for some type 1 error in the OT&E test equipment). These failures would represent a portion (which could be statistically sized) of the combination of α_1 and shipping induced failures. Transportation and handling failures can be tested separately, then factored to estimate α_1 . Special consideration of the test equipment itself in conjunction with a PMEL is warranted.



BDM-A-01-016-TR

Figure 11. OT&E Test Sensitive Decision Process

<u>Test Sensitive Element</u>	<u>Test Methodologies</u>
1. Initial Undetected Failures	<ul style="list-style-type: none"> a) Checkout upon receipt with b) and c) b) Transportation & handling tests c) Test equipment efficiency
2. Transportation and Handling	<ul style="list-style-type: none"> a) Handling procedures b) Accelerated transportation c) Mobility/deployment exercises
3. Periodic Test and Maintenance Induced Failures	<ul style="list-style-type: none"> a) System level, on/off b) Continuous on-equipment test sequence c) On-equipment test sequence on/off d) Continuous subsystem test (shop) sequence e) Subsystem test sequence (shop) on/off f) Flight line "tone" checks on-off g) How malfunctioned/when discovered tracking
4. Test Equipment Efficiency (α)	<ul style="list-style-type: none"> a) Maintenance/PMEL evaluation b) Fault injection c) FMEA fault identification

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Figure 12. Summary of OT&E Test Sensitive Elements (Tactical Air-to-Air Missile)

Test Sensitive Element

Test Methodologies

- | | |
|-------------------------------------|--|
| 5. Captive Carry
(non-operating) | a) Pre- and post-flight checkout
b) Time accounting
c) Failure tracking |
| 6. Surveillance Testing | a) Onsite storage, checkout
near end of OT&E
b) Pre-positioned storage
c) "Traveling Team" |
| 7. Test Firing | a) Live firing of rocket motors
and warheads
b) Live firing of "old" rocket
motors and warheads if "off
the shelf" |

SDM-A-81-016-TR

Figure 12. Summary of OT&E Test Sensitive Elements
(Tactical Air-to-Air Missile) (Concluded)

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6.4.3.2 Transportation and Handling.

Transportation and handling is test sensitive and can be measured by both accelerated and real-time means. Actual loading/unloading operations and transportation to and from the flight line can be repeated until failures occur. Deployment/mobility exercises can be conducted in real time. Care must be taken to account for time spent in the dormancy state and identified failures.

6.4.3.3. Periodic Test and Maintenance Induced Failures.

Failures induced by test equipment, maintenance, and the power on/off cycling activities effects are test sensitive and can be measured in several ways. Correlation among these results can assist in isolating the cause of the appropriate failures. Specific tests are:

- a) System level power on/off.
- b) On-equipment test sequence/BIT, continuous operation (attached to missile) until failure.
- c) On-equipment test sequence/BIT, on/off.
- d) Subsystem test station/BIT (Shop) test sequence, on/off.
- e) Subsystem test station/BIT (Shop) test sequence, continuous until failure.
- f) Flight line "tone" checks, on/off.

In addition, tracking normal maintenance reporting by when discovered/how malfunctioned codes can assist in isolating maintenance induced failures during the latter stages of IOT&E and FOT&E.

6.4.3.4 Test Equipment Efficiency.

Test equipment efficiency (type 1 error) can be "evaluated" in conjunction with PMEL and maintenance specialists. It can be tested by injection of known faults. The evaluation, above, in conjunction with a FMEA should give clues as to which faults to inject and which faults are likely to go undetected.

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6.4.3.5 Captive Carry.

Failures induced captive carry (for those subsystems which are non-operating) are test sensitive if failures are tracked and time is properly accounted for. Testing for non-operating failures in this dormancy mode requires pre- and postflight checkout (more data for "tone" check test) of the missile.

6.4.3.6 Surveillance Testing.

Surveillance testing is partially test sensitive. If the test program is long enough, a sample lot of missiles could be "checked out" after residing in storage for the entire test period. With very good advanced planning (and a little luck) some missiles might be pre-positioned in storage, on location, prior to the start of OT&E, in order to increase accrued storage time. This applies to FOT&E in particular. Another surveillance sampling technique that could be employed during FOT&E is to take a "snapshot" sample from various deployed, operational missile locations. In this case a traveling team, possibly augmented by onsite personnel, would completely "check out" a sample of missiles that had been in storage in the actual field environment. If the sample is large enough, a fairly accurate projection could be made. This would also eliminate error induced by shipping selected missiles back to a central location for surveillance test sampling. Care should be exercised in this regard if the maintenance concept involves a wooden round since failures could be induced by the test and checkout procedure.

6.4.3.7 Test Firing.

Firing rocket motors and warheads is test sensitive (with regard to dormancy) to a large degree. The nature of these subsystems is that they are dormant until fired. Every live firing failure of these subsystems

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could be attributed to at least a multimode dormant condition. In addition, if rocket motors and warheads are "off the shelf," as is often the case, then test firing "old" items could be used to assess dormant reliability.

6.5 EVALUATING DORMANCY EFFECTS.

The estimating techniques of table 1 and the test methodologies of figure 12 are both (in their own right) sufficient to "measure" all states of dormant reliability (inherent dormant reliability, operationally ready storage, non-operating transportation and handling, non-operating launcher carriage when applicable, and non-operating captive carry). The summation of all failure rates (by subsystem) weighted by the time spent in each dormant mode results in an overall dormant reliability value. This value in turn can be used to predict dormancy effects (see paragraph 3.4). Logistics effects such as manpower, spares, support equipment, etc., can be assessed by typical LSET methods. Operational reliability effects (due to dormancy) can be assessed in a two-step process. First, the critical failures must be identified and factored out of the overall dormant reliability (typical LSET, criticality analysis and MCSP, etc., methods apply) value. Then the resultant mission critical failures can be used in a flight success model or (probability of kill) probability chain.

Dormancy effects can also be generated by using the failure rates by state as previously defined in a simulation model (such as the ALCM availability model) or the life cycle profile could be "exercised" by proper selection of time in each state and probabilities for entries into each state. In each case, typical methods familiar to AFTEC apply.

6.6 EVALUATING THE WOODEN ROUND.

An example of this process is contained in annex C. This particular example was developed by the Martin Marietta Corporation and is a very

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good representation of the typical approach. In this example, the dormant failure rates are held constant for both the wooden round and the periodic test concept so that a comparison can be made--a valid approach.

Given only these conditions, the periodic test concept will always predominate in terms of a trade-off against a wooden round. The example breaks down at this point, however, in that no consideration was given to failures induced by test equipment and maintenance actions. With these factors included, the "saw tooth" curve (see figure 13) will shift downward. In addition, reliability growth will shift both curves upward.

Thus, evaluation of the wooden round boils down to a very close examination of induced failures and reliability growth.

The reliability achieved by the periodic test concept lowered by induced failures and the associated costs (maintenance, spare parts, support equipment, and facilities, etc.) can be compared to the reliability achieved by the wooden round and its associated costs (spare missiles necessary to meet the required operational capability). The estimating and testing techniques for induced failures previously presented become critical in this evaluation.

Additional consideration should be given to reliability growth projections (a very careful evaluation is necessary) in comparison to required operational capability and the spare missiles necessary to meet and maintain it, both before and after "growth".

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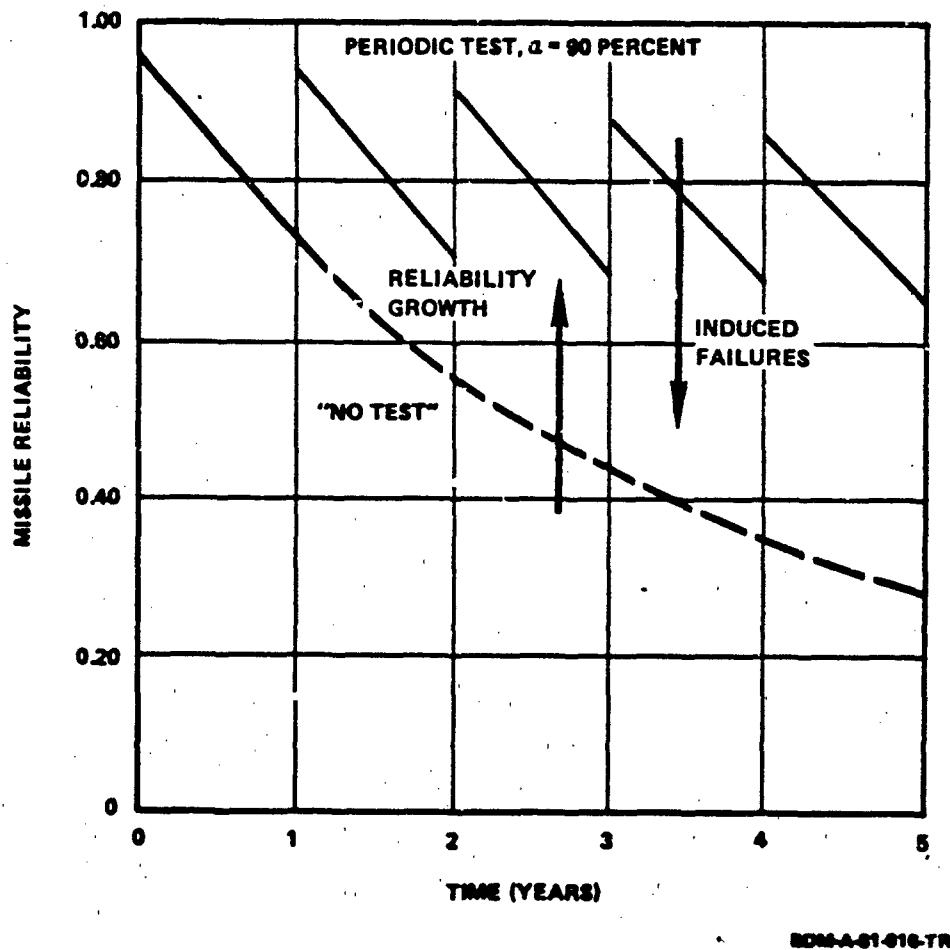


Figure 13. Example Missile Reliability after 5 Years of Dormant Deployment Under "Wooden Round" and Periodic Test Concept (Does Not Include Type 2 and 6 Failures)

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SECTION VII DATA SOURCES

7.1 OVERVIEW.

During any new missile systems's dormant reliability evaluation, obtaining current dormant reliability data on comparable systems or subsystems is judicious, and, of course, requisite if a comparability analysis is to be performed. However, there are no major DoD standard, automated data systems specifically designed to accumulate or output dormant reliability data. For the most part, data pertaining to dormant reliability characteristics of missile systems are fragmented and spread throughout a myriad of documents, contractors, individual missile program management organizations, and lower level DoD organizations. There may be a limited usefulness for obtaining failure data for missiles from the Air Force Base Level Maintenance Data Collection System (MDCS), but a thorough understanding of the system code conventions is required as well as a structured analytical approach to the data manipulation and definition. It is usually easier for the reliability analyst to directly contact a comparable missile system's program office or responsible Air Logistic Center for data or other points of contact. This section defines some of the major documents, points of contact, or data systems that can be used as a starting point in a data acquisition effort. The reader is also referred to the fairly extensive reference list in annex F.

7.2 AIR FORCE DATA.

Missile management within the Air Force (and Navy, in most cases) is somewhat fragmented. Air Logistics Centers (ALCs) are assigned item management for component/subsystems (e.g., Odgen ALC for explosive/pyrotechnic services, Warner-Robins ALC for guidance systems, etc.) If a life surveillance test program for a missile system is initiated and maintained, it is usually supported through separate ALCs, each with somewhat unique data collection and reporting systems.

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For example, the Maverick missile program has a long term storage surveillance and periodic inspection program being maintained by the ALC at Hill AFB, Utah. The primary data collected concerns the effects of storage on the three major subsystems of the missile: propellant, guidance, and hydraulic actuation system. The ALC is supported by engineers who direct the reliability, surveillance and inspection program, and a contractor (Ultrasystems, Inc.) who performs data collection, analysis, and reporting tasks for the system manager. Ultrasystems also performs the data collection, analysis and reporting tasks for the fleet aging surveillance program for the Minuteman II missile. Ogden ALC also maintains an extensive data bank on a number of pyrotechnic surveillance programs.

A surveillance testing model designed for use in the AMRAAM program is available from AFLC/AFALD. The model may be used to analyze the inventory availability, surveillance testing workload, and repair workload of other systems subject to long term storage and periodic inspection.

Initial storage/surveillance testing for the ALCM system is being performed by AFSC/ASD/YEE. Under this program two complete ALCM airframes are undergoing an operational environment test (OET), and two ALCM engines mounted in aft missile sections are being rotated through 90 days of storage and 90 days of outside environment conditions.

7.3 ARMY DATA.

A large majority of the Army missile reliability data is stored at the Redstone Arsenal in Huntsville, Alabama. However, it is generally recommended that individual missile program managers be contacted for specific data. Additional data sources may be found at the U.S. Army Research and Development Command, Dover, NJ, or the U.S. Army Readiness Command, Rock Island, IL. One of the more definitive studies on missile dormant reliability was accomplished with the Raytheon Company study on the "Storage Reliability of Missile Materiel Program" for MIRADCOM initiated in 1974. The original series of publications were produced in 1976 and updated in 1978.

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The Lance missile reliability data is being managed through the MIRADCOM/LANCE PMO, at Redstone Arsenal. In this program, deployed missiles are tracked through a special data collection system that helps to validate design criteria using piece part data and working up to the system level.

One of the most important focal points for dormant reliability data is the MIPADCOM/Product Assurance Division at Redstone Arsenal. This division currently maintains the Non-Operating Reliability Data Bank for missile systems (at this time the only known automated data bank built specifically to manipulate only non-operational reliability data). Although the data bank is currently based upon a piece part level of data storage and reporting, efforts are currently underway to improve the files for data extraction to include the capability of collating piece part data to develop a system storage reliability data base.

7.4 NAVY DATA.

The Navy Maintenance Data System is the most complex and detailed of the three Services. However, the data collected under the formal recording procedures (similar to the Air Force MDC system) does not contain specific dormant reliability data. Again, particular reliability information about a specific missile or missile subsystem should most likely be sought from Navy system program offices or from specific test sites or organizations.

For instance, the Naval Ordnance Station at Indian Head, Maryland has facilities for accelerated environmental testing of solid rocket motors. Accelerated testing is accomplished at twice the normal environmental temperature cycles, and data has been gathered for several motor types.

The Naval Weapons Center at China Lake, California is one of the major development and test facilities for Navy missiles. In particular, much data has been gathered on anti-radiation and air-to-air missiles at this site. For cruise missile comparability data, the Navy Fleet Analysis Center at Corona, California is currently collecting Harpoon data and has recently developed storage reliability data.

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7.5 DATA SYSTEMS LIMITATIONS.

It is readily apparent from this discussion that data pertaining to dormant missile reliability are very limited. What data exist are fragmented in various locations, generally on a program basis. The Services' maintenance data collection systems are not structured in a way that allows dormancy information to be captured and reported. It is fairly obvious that data sources will present one of the greatest difficulties in any assessment of dormant reliability.

With the current trends in missiles, dormant reliability, and the acquisition process which supports these trends, the challenge then becomes one of effecting coordination among agencies to maximize the usefulness of existing data/data systems and to improve and potentially standardize the process over time toward the same end.

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SECTION VIII DORMANT RELIABILITY ASSESSMENT APPROACH

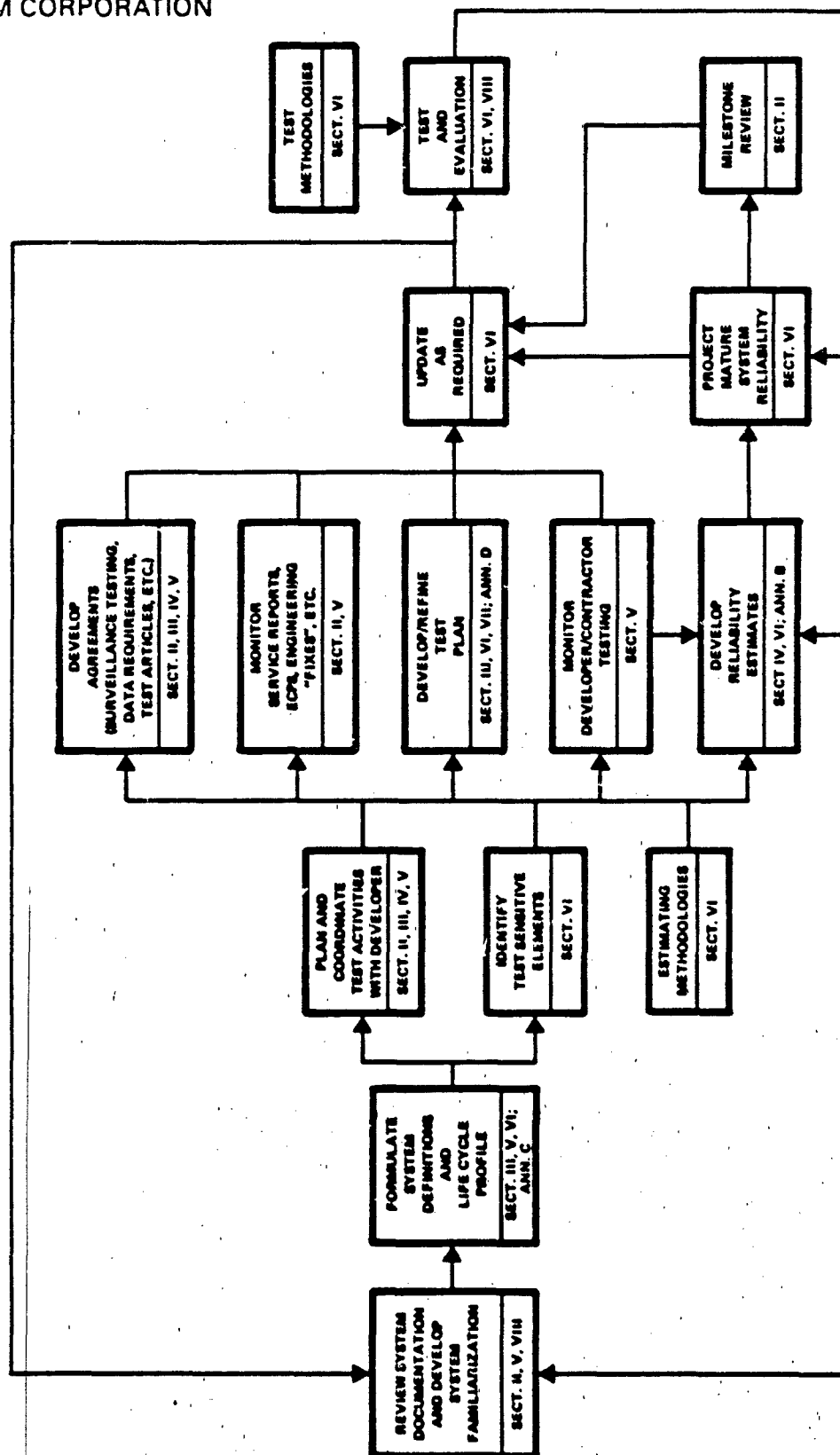
8.1 OVERVIEW.

The general approach to assessing dormant reliability is to build upon the results of all previous chapters in an iterative process -- one which is in consonance with the development process milestones and activities (see figure 5). The central methodology issues of estimating and testing dormant reliability are provided in section VI, particularly table 1 and figures 11 and 12. These methodologies in combination with the (no less critical) necessary planning, monitoring, and coordination activities essentially frame the analytical approach.

Figure 14 provides an overview of the assessment approach. Each activity block in the figure is keyed to the portions of the report which describe and develop the necessary prerequisites. The process "loops" in a way which covers the missile system's entire life cycle. The products of continuing planning and milestone reviews as well as results of the comprehensive test and evaluation program are fed back to permit continuous iteration and update. It is a process which logically tracks reality.

8.2 IMPLEMENTATION GUIDELINES.

The approach for assessing missile system dormant reliability as part of a comprehensive test and evaluation program is depicted in figure 14. Preceding sections have provided detailed background discussions within the major topic areas necessary to formulate the approach. This set of general guidelines is provided for use in employing the approach. It is not intended as a "cookbook" approach nor is it meant to represent a detailed checklist. In fact, it should be regarded as a series of initial points from which the analyst can depart to accomplish necessary tasks in the dormant reliability assessment program.



BDM-A-81-018-TR

Figure 14. Dormant Reliability Assessment Approach

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8.2.1 Planning.

The guidelines for the planning phase have been divided to reflect the early or advanced planning and the detailed planning associated with preparation for conduct of the IOT&E.

8.2.1.1 Advanced Planning.

- a) Review program documentation from the SPO and contractor for critical questions and areas of risk associated with dormant reliability.
- b) Review operations and maintenance concepts for background in dormant reliability testing.
- c) Ensure that the failure definitions to be applicable throughout testing are incorporated in appropriate program documentation, e.g., PMD, TEMP, TPO, Contract, etc.
- d) Formulate the life cycle profile model.
- e) Ensure that a piece part dormant reliability prediction is accomplished by the SPO or contractor. Review the prediction if one is already accomplished.
- f) Review system design for dormant reliability considerations.
- g) From initial reliability predictions, determine preliminary number of assets for system surveillance tests during IOT&E and recommend that the assets be incorporated into the contract and SPO budget.
- h) Review the contract to determine if failure analyses are required. If failure analyses are not included, recommend contract amendment to include analyses.
- i) Review the contract and DT&E test plan for contractor accelerated testing of piece parts and subsystems. If accelerated testing is not included, recommend contract addition.

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- j) Ensure test objectives in the IOT&E test plan include accelerated and surveillance testing.
- k) Ensure coordination of MOEs for the accelerated and surveillance tests.

8.2.1.2 Detailed Test Planning.

- a) Review the current design and the current operations and maintenance concepts to update the life cycle profile, IOT&E objectives, and test methodology.
- b) Review failure analyses.
- c) If the system incorporates solid rocket motors, check with Navy Ordnance Station for information on testing.
- d) Update the reliability prediction due to design or operation and maintenance concept changes.
- e) Review the Failure Modes, Effects, and Criticality Analysis (FMECA) for updating IOT&E test plan objectives and methodology.
- f) Ensure initiation of subsystem and component accelerated testing.
- g) Ensure initiation of surveillance tests of subsystems and components.
- h) Accomplish detailed test planning methodology for appropriate system tests to address sensitive areas.
- i) Ensure that assets are identified for above tests.

8.2.2 IOT&E.

- a) Review current design and current operations and maintenance concepts.
- b) Update the life cycle profile, as necessary.
- c) Review failure analyses.

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- d) Update dormant reliability prediction for changes in system design and/or operations and maintenance concept changes.
- e) Start system surveillance tests with sample partitioned to examine previously determined sensitive test areas.
- f) Compare DT&E and early component and subsystem IOT&E accelerated and surveillance test data to preliminary IOT&E data.
- g) Calculate the failure rates and compare to T/S/G and predicted reliability.
- h) Document deficiencies and review engineering fixes of the deficiencies.
- i) Compare test data for failure rates to scheduled inspection period.
- j) Review and analyze test equipment efficiency.

8.2.3 FOT&E.

- a) Refine life cycle profile, as necessary.
- b) Develop FOT&E objectives if different from IOT&E objectives.
- c) Establish new MOEs if necessary.
- d) Continue surveillance tests.
- e) Update failure rate and compare to predicted failure rate.
- f) Update test calculated failure rate and compare to predicted failure rate.
- g) Statistically analyze and compare IOT&E and production failure rates for statistical differences.
- h) Statistically analyze DT&E (accelerated and surveillance tests) and production failure rates for statistical differences.

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SECTION IX CONCLUSIONS AND RECOMMENDATIONS

9.1 CONCLUSIONS.

The following conclusions are offered as a result of this study effort.

- a) The notion of dormancy is non-trivial, and well-structured definitions of dormant-related terminology, within the context of the specific missile system being developed, are essential to properly estimate and test for dormant system reliability.
- b) Reliability prediction through both analytical estimation and test techniques is possible. Although some areas have not been validated, they look promising. Both types of techniques cover the total spectrum of dormant reliability assessment. Therefore, begin by updating initial contractor estimates and transition to testing when practical.
- c) Early formulation of the missile system's life cycle profile model is essential to the entire process of defining dormancy, structuring a comprehensive test program, and assessing the effects of dormancy on operational reliability and logistics reliability.
- d) A disciplined approach has been provided which can be used as the framework for developing a structured test methodology for a specific missile system's dormant reliability assessment program.
- e) Reliability prediction based upon the piece part count methodology should not be ignored. During the early planning phase, it may provide the only source of available data.
- f) Early AFTEC involvement during the conceptual phase of the missile system acquisition cycle is essential.

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- g) The critical element of "dormant failure rate" for missile systems maintained under a wooden round concept appears to be induced failures. System reliability can be improved with a periodic test concept provided the induced failure rate can be held to a low level.

9.2 RECOMMENDATIONS.

During the course of this study, it has become increasingly apparent that only the surface of dormant reliability has been scratched. Each new report, journal article, etc., provides a bibliography or reference list sufficient to warrant pursuit of the subject for several more days or weeks. Five specific areas are worthy of further investigation.

- a) Validation of the proposed methodology should be accomplished as soon as possible. It is anticipated that such a task probably cannot be accomplished in the initial attempt. The approach relies heavily upon outside (of AFTEC) interfaces to provide input; it will take time to develop such interfaces.
- b) There is an urgent need to conduct a comprehensive survey of relevant data bases (e.g., USAF MDC, Army, Navy, contractor, etc.) and characterize their similarities and dissimilarities. It is strongly suspected that the manner in which failure data are collected and maintained precludes any meaningful assessment of dormant reliability.
- c) A comprehensive missile system/subsystem comparability survey is necessary. The product of such an effort would provide valuable input for defining and establishing structured data bases compatible with reliability prediction requirements. It would also provide a convenient and valuable source of similarity data at the missile system/subsystem level for use in early comparability

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analyses and selection of appropriate sources for similar system/subsystem data.

- d) The area of accelerated system testing warrants further study. There is insufficient data at this time to enable any conclusion to be drawn, with reasonable confidence, about the utility of such testing. It appears to be feasible in some areas (e.g., environmental cycling) but not in others (e.g., power on/off cycling), except in limited specific cases.
- e) "Community" consistency regarding the definition of dormancy (and thus the application of various techniques and methodologies) is necessary. It is possible that the "community" could benefit from an AFTEC-sponsored conference similar to the Air Force-wide Cost of Ownership definition process sponsored by AFTEC in 1975. Ambiguity could be reduced, cross utilization could be enhanced, and common data base structures established.

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ANNEX A FAILURE RATE CALCULATION PROCEDURES

A.1 INTRODUCTION.

Parts count and part stress analysis prediction methodologies were briefly discussed in section IV. They were presented as applicable reliability prediction techniques for use during the design and early development phases in the weapon system acquisition process. The techniques are widely accepted and periodically reviewed and refined, as necessary, as part of the Rome Air Development Center Reliability Program. This annex represents a compilation of information from references 34, 36, and 37. It is intended to provide a sufficiently relevant discussion to familiarize the AFTEC analyst with the methodology, not to provide detailed instructions on the use of the techniques.

A.2 PART FAILURE MODELING.

Prediction is an integral task of reliability development programs. The basic concept which underlies reliability prediction and the calculation of reliability numerics is that system failure is a reflection of part failure. Therefore, a method for estimating part failure rates is needed. The most direct approach involves the use of large scale data collection efforts to determine the relationships (i.e., models) between engineering and reliability variables. This approach utilizes controlled test data to:

- a) Derive relationships between design and generic reliability factors, and
- b) Develop factors for adjusting the reliability to estimate field reliability when considering application conditions.

These data were reduced through physics-of-failure techniques and included in MIL-HDBK-217B in a form suitable for estimating stress-related failure rates. MIL-HDBK-217B provides guidance during design and allows

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individual part failure rates to be combined within a suitable system reliability model to arrive at an estimate of system reliability.

Part failure models vary with different part types. However, their general form is:

$$\lambda_{\text{part}} = (\lambda_b)(\pi_E)(\pi_A)(\pi_Q) \dots (\pi_n)$$

where:

λ_{part} is the total part failure rate.

λ_b is the base failure rate. The value is obtained from reduced part test data for each generic part category, where the data is generally presented in the form of failure rate versus normalized stress and temperature factors. The part's primary load stress factor and its factor or safety are reflected in this basic failure rate value. The value of λ_b is generally determined by the anticipated stress level (e.g., power and voltage) at the expected operating temperature. These values of applied stress (relative to the part's rated stress) represent the variables over which design control can be exercised and which influence the item's ultimate reliability.

π_E is the environmental adjustment factor which accounts for the influences of environments other than temperature, and is related to the military operating condition (e.g., vibration, humidity, etc.) under which the item must perform. Twenty-three of these environmental classes have been defined in MIL-HDBK-217B. Depending upon the specific part type and style, the value of π_E will vary from 1.0, the ground benign environment, up to more than 700. The missile launch environment is one of the most severe and generally dictates a high value of π_E .

π_A is the application adjustment factor. This factor depends on the application of the part, and takes into account secondary stress and application factors that are considered to be "reliability-significant."

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π_Q is the quality adjustment factor used to account for the degree of manufacturing control with which the part was fabricated and tested prior to its shipment to the user. Many parts are covered by specifications which have several quality levels.

π_n is the symbol for a number of additional adjustment factors which account for cyclic effects, construction class, and other factors that modify failure rate.

The data used as the basis to develop MIL-HDBK-217B consist of controlled test data, field data, and expert opinion. The controlled test data directly relates stress/strength variables on a wide variety of parts and is suitable to establish the base failure rates (λ_b).

Base failure rates, in general, have been established from tests conducted under accelerated stress conditions which speed up the aging process. Stress levels were defined, time-to-failure data was recorded, and all failure modes were identified. Part failure rates derived under accelerated stress conditions were then converted to normal operating conditions through knowledge of the test acceleration factors. Acceleration factors were determined through detailed analyses of accelerated test failures involving physics-of-failure studies to determine mechanisms of failure.

The aging process has been characterized via rate process models, attributed to Arrhenius and Eyring, that are a result of both empirical data and theoretical considerations. These rate process models form the basis of physics-of-failure and accelerated test techniques and provide a relationship between stress (electrical and thermal), time, and failure rate. The Arrhenius model takes the following general form:

$$\lambda_b = K_1 e^{-C_1/T}$$

K_1 = a constant

C_1 = a constant depending on the activation energy of the individual part type failure mechanism

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T = absolute temperature in $^{\circ}\text{K}$.

The Eyring model includes an additional temperature factor (T):

$$\lambda_b = K_2 T e^{-C_2/T}$$

Neither of these relationships have been proven to be exact models of the time-stress combination with respect to failure rates. They are merely approximations, useful in conjunction with a certain set of conditions.

Although laboratory controlled test data provide valuable information as to the upper limit or potential reliability of parts, application factors and the use environment prevent realization of this potential. Field data collection and analysis efforts have indicated part failure rates well above those determined from laboratory testing. To account for the adverse influence of the application environment and to align the base failure rate (λ_b) with field experience, a series of π factors, as previously defined, have been developed to account for specific production, operation and maintenance, and application environment stress factors.

A.3 RELIABILITY PREDICTION TECHNIQUES.

A prediction of reliability is obtained by determining the reliability of the lowest system level item and proceeding through intermediate levels until an estimate of system reliability is obtained. The prediction methodology is dependent on the availability of: (1) accurate evaluation models that reflect the reliability connectivity of the lower level items and (2) substantial failure data that has been analyzed and reduced to a form suitable for application to the low level items.

There are various formal prediction procedures, based on theoretical and statistical concepts that differ in the level of data on which the prediction is based. The specific steps for implementing these procedures

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are described in detail in reliability handbooks. Among the procedures available are parts count methods and stress analysis techniques.

The parts count method provides an estimate of reliability based on a count by part type (e.g., resistor, capacitor, integrated circuit, transistor, etc.). This method is applicable during early design studies where the degree of design detail is limited. It involves counting the number of parts of each type, multiplying this number by a generic failure rate for each part type, and summing up the products to obtain the failure rate of each functional circuit, subassembly, assembly and/or block depicted in the system block diagram. The advantage of this method is that it allows rapid estimates of reliability in order to quickly determine the feasibility (from the reliability standpoint) of a given design approach. The technique uses information derived from available engineering information and does not require detailed part-by-part stress and design data.

The stress analysis technique involves the same basic steps as the parts count technique. However, the stress analysis technique requires the use of detailed part models plus calculation of circuit stress values for each part prior to determining its failure rate. Each part is evaluated in its electrical circuit and mechanical assembly application based on an electrical and thermal stress analysis. Once part failure rates are established, a combined failure rate for each functional block in the reliability diagram can be determined. To facilitate calculation of part failure rates, worksheets based on part failure rate models are normally prepared to aid in the evaluation. These worksheets are prepared for each functional circuit in the system. When completed, these sheets provide a tabulation of circuit part data including: part description, electrical stress factors, thermal stress factors, basic failure rates, the various multiplying or additive environmental and quality adjustment factors, and the final combined part failure rates. The variation in part stress factors (both electrical and environmental) resulting from changes in circuitry and packaging is the means by which reliability is controlled during design.

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Both the parts count and the stress analysis methods of predicting reliability rely on part failure rate data obtained from MIL-HDBK-217B. However, not all parts used in electronic system design are included in MIL-HDBK-217B. For those parts not covered by 217B or where little supporting data is available, care must be exercised in estimating their failure rates. In general, estimating failure rates for parts having limited failure data involves comparative evaluations or special tests and studies.

A.4 SUMMARY.

The part modeling methodology and reliability prediction techniques described in this annex have been widely accepted and are applicable during the early design phase of electronic equipment. Unfortunately, similar methodologies for nonelectronic components and equipment are not as well defined, although some efforts have been undertaken by the Rome Air Development Center and the Redstone Arsenal. Familiarity with early reliability prediction techniques will permit the operational test analyst to use development contractor data, if desired, with some acceptable level of confidence.

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ANNEX B

MISSILE SYSTEM DORMANT RELIABILITY DEGRADATION

B.1 INTRODUCTION.

The need for addressing dormant reliability and the effects of dormancy was discussed in section II. This annex will provide a brief summary of some of the principal problem areas associated with dormant reliability degradation. The causes of typical missile system failures are treated generally in rather broad categories relating to design, manufacturing, and transportation and handling. Examples of specific representative failure modes are discussed for hydraulic, electronic, electromechanical, and solid propellant components.

B.2 DESIGN DEFICIENCIES.

The trend in missile systems, as discussed in section II, is toward greater sophistication, complexity, and periods of dormancy. Therefore, the first step toward achieving high dormant reliability is initially designing the missile system to withstand long periods of dormancy.

Careful selection of components and materials is an essential element in any attempt to minimize design deficiencies. The coupling of dissimilar metals should be avoided wherever corrosion is anticipated as a result of such coupling. For example, the so called "purple plague" which appears in electronic equipment when aluminum wire is bonded to gold-plated posts should be considered a design deficiency with respect to dormancy.

Designs which permit continuous physical stress on components can result in cracking which may, in turn, be susceptible to breakage or the formation of corrosion. Rubbing surfaces will also provide an area where corrosion can begin. Careful attention in the system design can minimize or eliminate the corrosion potential caused by activating a system and then returning it to storage.

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The coating of electronic components and/or complete systems is important. The ingress of contaminants into components or systems is a major cause of storage failures. These contaminants may cause oxidation, corrosion, or a stray conduction path for current in electrical components. In some cases, outgassing of materials used in coating/encapsulating may cause problems. Also, the flaking of metallic and non-metal finishes may result in contamination of fluids.

B.3 MANUFACTURING DEFECTS.

A primary cause of reliability degradation due to manufacturing seems to be insufficient cleaning of contaminants (water, dirt, solder, cleaning solutions, etc.) from components. Also, the improper assembly of electronic components (e.g., too much or too little pressure in making terminal connections) can cause breakage or intermittent opens. Inadequate solder connections which provide excess solder and solder fluxes can result in stray conductive paths. Most previous studies on dormant reliability have found that a substantial proportion of the failures were caused by poor quality control of the manufacturing and assembly processes. Failures were analyzed after periods of storage or accelerated testing to determine their causes. Quite often the failure was attributed to the continued effect of a manufacturing error acting over time. Some authors have indicated that failures of this type may be caused by aging. However the failure may be categorized, it is apparent that proper manufacturing and assembly can minimize the severity of system failures during dormant storage.

B.4 TRANSPORTATION AND HANDLING INADEQUACIES.

Transportation and handling of missile systems has been a major cause of damage and subsequent system failure. Several instances of mishandling have been recorded reflecting serious damage inflicted as a result of missiles being dropped from fork lifts. On the positive side,

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the Sergeant missile was road tested over more than 1,100 miles of various road conditions (e.g., improved, unimproved, and asphalt). Two missiles were used in the test and survived with no problems encountered, indicating that handling problems can be overcome. Of course, container design is an inherent factor affecting the degree to which missile systems can withstand frequent transportation and handling.

B.5 EXAMPLES OF DORMANT FAILURE CHARACTERISTICS.

There are several causes of system, subsystem, and component reliability degradation while in a dormant state. Quite often, the dormant failure modes are the same as those found in the operating environment although the failure rate may be different. The following discussion is intended to provide insight into some of the more prevalent component failure modes for hydraulic items, electronic devices, electromechanical systems, and solid propellants.

B.5.1 Hydraulic Systems.

There is evidence to indicate that hydraulic fluid can withstand long storage periods without degradation provided it is free of contaminants. Fluid from a B-24D aircraft was examined after 17 years in the Libyan desert and found to meet the original specifications. If the hydraulic system is not exercised during storage and, therefore, is not generating contaminants (particles liberated because of moving parts), then the fluid should withstand the anticipated dormant period.

Hydraulic seals may experience problems due to breakaway friction, the friction encountered when a rod or part moves through a seal. This friction can increase over time, and if the increase is large relative to the working pressure of the system, then a design deficiency may exist. In contrast, equipment items such as servovalves, actuators, pumps, and accumulators can probably be stored for periods of at least five years with little chance of serious degradation as long as the hydraulic fluid is clean.

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It is apparent that preparation is the most important consideration in storing hydraulic systems. The fluid used must be clean, and care must be taken when filling and assembling the system to ensure that no contaminants are introduced. Fittings must be tight, and the exterior must not provide for any chance of corrosion through cracks, scratches, or stress. Problems may occur in storing hydraulic systems if they are to be exercised during storage and returned to the dormant condition. Usage generates contaminants in the system by generating particles which can agglomerate and cause degradation and/or failures. If operation during storage is required of the system, then specific engineering designs must take operation into consideration. Perhaps the system should be purged and refilled with new fluid.

B.5.2 Electronic Systems.

Several previous studies have concluded that the failure modes found in the operational environment are essentially the same as those resulting from dormancy for electronic systems. Furthermore, most failures result from the manufacturing process. A Martin Marietta study (reference 29) provided the following breakout of electronic part non-operating failure modes:

Bonding/Welding	21.5%
Photoetching	17.2
Transportation and handling	12.9
Seal aging	12.9
Expansion coefficient	12.9
Conductive cement	8.6
Defective hermetic seals	4.3
Plating	4.3
Soldering	4.3

These modes are directly associated with manufacturing processes and/or improper design.

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Electronic part failure modes are dependent upon the environment and the storage condition of the component. Failure modes for semiconductors are the same in storage as in operation. In some components the failure occurrence is independent of the application environment. For others it may be time-related and environment-dependent. If the failure is independent of the application environment, then failures have the same rate of occurrence in operation as in storage. If the failure occurrence is dependent upon the application environment, then the predominant failure modes are bond or metallization defects which progress to failure due to temperature or mechanical stress. If the failure occurrence is time and environment related, then the failure modes are more likely to appear as metal migration, intermetallic compound formations, corrosion, etc.

Electronic part failure modes also tend to be part dependent. Transistors have failures that are generally categorized by opens, shorts, or parameter changes. Resistors experience opens, corrosion, cracks, and film flaking. Current leakage is the major problem in diodes and may be caused by any of several factors. Defective seals or cases are the primary faults in capacitors. The usual failure modes within microelectronics are opens, shorts, and current leakage.

B.5.3 Electromechanical Systems.

Electromechanical systems generally consist of gyros, accelerometers, switches, relays, motors, generators, and starters. These devices use electrical forces to accomplish mechanical functions. They are used in missile systems to accomplish functions such as guidance, ignition, safe and arming, and valve actuation. Gyros experience a variety of problems including spin bearing lubricant dry out, magnetic variation, and bearing adhesion. Most failures in accelerometers occur through contamination, and they do not appear to be significantly different than operating failures. Switch failures definitely appear to be age related and include corrosion of contacts and other metal surfaces, spring relaxation, and O-ring aging.

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Dormant failure data for relays was extremely limited. However, operating failures are attributed primarily to contact welding due both to the contact material and the current passing through them. It has been recommended that relays be operated occasionally in storage at no-load conditions. Dormant failure mode data is also not well documented for motors, generators, and starters. The usual failure mode found is outgassing of the lubricant or coil impregnant which causes corrosion in the brushes, armature, etc. It is assumed that the predominant failure mechanisms are the same as those in gyros and switches.

B.5.4 Solid Propellants.

As a class, solid propellants can be stored for extended periods. Four BOMARC missile motors which were between 120- and 123-months-old were all successfully fired. Inspection before firing indicated some slight separation of liners from cases, but this problem did not affect the firing. In general, the failure modes for solid propellants include propellant cracking, propellant separation from the case, and chemical decomposition. These failure modes do not usually result in complete failure. The failure modes are caused by low temperatures, elasticity loss and expansion of propellant at high temperature, contamination, slow chemical decomposition, and rough handling. There appears to be some increase in failures in single thrust, double base propellant and dual thrust, composite propellants with age. For dual thrust, double base propellants, there does not appear to be an aging trend. The aging trend can be slowed by using an appropriate stabilizer that will reduce the rate of chemical decomposition of the propellant. Design deficiencies are a more serious problem of dormant reliability degradation than the materials themselves.

B.6 SUMMARY.

The principal contributors to low dormant reliability tend to be missile system design deficiencies and manufacturing process defects.

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However, proper quality control of the manufacturing process can reduce many of the failures which occur under dormant conditions. Careful design practices can minimize failures through proper selection of materials and parts. Better missile system design can also be achieved by thoroughly understanding the operations and maintenance concept and the environment in which the system is to be employed. Proper handling and measures to protect the system from particulate contamination and extreme environmental conditions will also contribute to improved dormant reliability.

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ANNEX C

AN EXAMPLE OF THE LIFE CYCLE MODELING METHODOLOGY

C.1 INTRODUCTION.

The methodology presented in section VIII cannot be considered new or unique. Variants of the process have been presented in several references and, while minor differences may have existed between various authors' presentations, the underlying philosophical approach has always been the same. The approach presented in reference 46 is considered particularly interesting because it reflects the use of many of the concepts and techniques which have been discussed in this study. It utilizes part failure rate data and reliability prediction techniques for both electronics and nonelectronic components in a hypothetical missile system, accounts for various application environments, and estimates missile flight reliability for alternative maintenance concepts. The reference 46 discussion is provided in this annex as an example of the utility of the life cycle modeling approach.

C.2 LIFE CYCLE MODEL.

The basic modeling techniques required for the prediction of system reliability in the dormant mode were established and validated in 1967 and updated in 1973. These basic techniques were primarily for electronic systems or the electronic portion of a system with a heterogeneous part mixture. This was due to a general lack of well-documented dormant failure rate data on nonelectronic components. With the addition of the nonelectronic dormant failure rates generated during this study, life cycle models can be applied to entire systems with much more accuracy.

The life cycle model evaluates system reliability in terms of system design characteristics and useful deployment schemes, which include the effects of:

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- a) Service life environmental (deployment) modes
- b) Expected time in each mode
- c) Failure detection capability of the system
- d) Accumulation of failures from the operating and dormant environments
- d) Frequency of periodic test and checkout.

A simplified life cycle model is shown in figure C-1 for a theoretical missile system which is periodically monitored for failures after deployment. From the figure, note that the predicted reliability of the missile, after being in a dormant environment, is a function of:

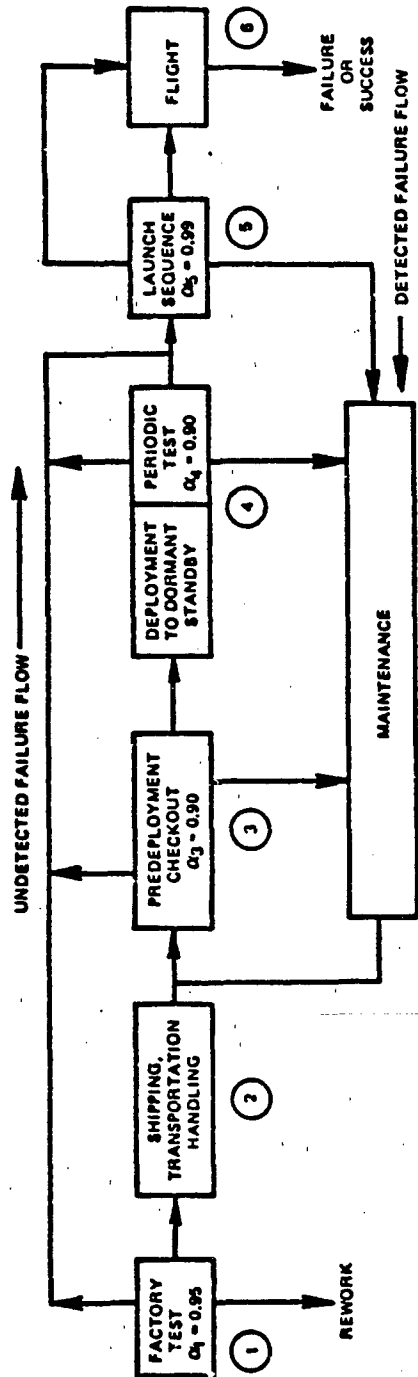
- a) The undetected failures accumulated from prior modes
- b) The dormancy failure rate and time in dormancy
- c) The effectiveness or testability factor, α_i , of the system.

An example relating to this model will be given in the following paragraphs.

C.3 DORMANCY MODELS.

As evidenced by figure C-1, the life cycle profile of a system encompasses several phases such as factory test, deployment, and final end use. Therefore, within the overall life cycle model, individual submodels can be developed to depict the system reliability during these different phases. For many military systems the deployment mode initiates a long period of dormancy before the system is used in its intended mission. Two basic types of deployment techniques exist for dormant systems: the "no test" concept and the "periodic test" concept. Dormancy models have been developed for each of these deployment techniques to provide accurate estimates of system reliability at any time during the dormant period.

The "no test" model, used in conjunction with the most basic deployment survival technique, predicts the reliability of systems designed to the "wooden round" concept. Under this concept, the system deployed may



1 UNDETECTED FAILURES THROUGH MODE 4: $F_4 = 0.05 \lambda_1 t_{D1} + 0.10 (\lambda_2 t_{D2} + \lambda_3 t_{D3}) + 0.90 \lambda_4 t_{D4}$

SYSTEM RELIABILITY THROUGH MODE 4: $R_4 = e^{-F_4}$

2 FAILURES DETECTED DURING MODE 5: $F_5 = 0.99 (F_4 + \lambda_5 t_{D5})$

PROBABILITY OF PASSING MODE 5: $R_5 = e^{-F_5}$

3 UNDETECTED FAILURES PASSED TO MODE 6: $F_6 = 0.01 (F_4 + \lambda_5 t_{D5})$

FLIGHT RELIABILITY: $R_6 = e^{-F_6}$

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Figure C-1. Life Cycle Model for Dormant Missile with Periodic Test

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be in a dormant state for as long as 10 years; it is never tested, or is tested just before being used in its intended mission. For some of the less complex systems, the utility, applicability, and simplicity of this technique provides a most effective deployment concept. However, as system complexity increases, other means must be found to assure that an acceptable level of reliability is maintained throughout deployment.

The second deployment survival technique is used for higher complexity systems which can experience considerable degradation over long periods of dormancy. In this technique, which is the periodic test concept, the deployed system is tested at periodic intervals, such as every six months, and any necessary repairs are made after each test.

A third deployment technique, the constant monitor concept, has been used occasionally but will not be considered in this analysis. With this technique the system is constantly operating at very low level power such that failures are detected immediately.

To visualize the differences between the two basic deployment survival techniques, examples are provided which compare the effects and results of each method through respective life cycle mathematical models. A hypothetical tactical missile will be evaluated during its deployment period. The missile is constructed of high reliability electronic components and standard grade nonelectronic items. Also, the missile is to be contained in a controlled dormant environment during deployment. Operating and dormant failure rates for the individual parts/components were derived from field measurement data and part failure modeling techniques. Table C-1 contains the combined electronic and nonelectronic component failure rates in the ground operating and dormant configurations.

Table C-1.

Electronic and Nonelectronic Failure Rates For Hypothetical Missile

Part Category	Dormant Failure Rate (failures/10 ⁶ part-hours)	Operating Failure Rate (failures/10 ⁶ part-hours)
Electronic	14.876	1186.967
Nonelectronic	14.359	880.553
Totals	29.235	2067.520

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In referring to figure C-1, mode 4 of the life cycle model (deployment) is the only variation to be considered in the following examples. Therefore, the undetected failures through mode 3 can be calculated to determine the missile reliability, R_3 , at the end of mode 3 or at the beginning of deployment:

$$F_3 = (1 - \alpha_1) \lambda_E t_{E_1} + (1 - \alpha_3) (\lambda_D t_{D_3} + \lambda_E t_{E_3})$$

where:

F_3 = Expected failures through mode 3

α_1 = 0.95 = Test efficiency of factory test

λ_E = 2067.520 failures/ 10^6 part-hours = System operating failure rate

t_{E_1} = 340 hours = Total operating time prior to shipment

α_3 = 0.90 = Test efficiency of predeployment checkout test

λ_D = 29.235 failures/ 10^6 part hours = System dormancy failure rate

t_{E_3} = 5 hours = Total operating time during predeployment checkout

The expected failures prior to deployment can now be estimated:

$$F_3 = [0.05] \left[\frac{(2067.520)(340)}{10^6} \right] + \left[\frac{(29.235)(720) + (2067.520)(5)}{10^6} \right] [0.10]$$

$$F_3 = 0.0383$$

System reliability just prior to deployment can now be calculated and is:

$$R_3 = e^{-F_3} = 0.962.$$

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C.3.1 No Test Concept

If the "no test" concept is chosen for the missile, then the system will remain in a dormant, unenergized state throughout the deployment phase of its life cycle.

No system failures will be detected during this period, and the total undetected failures which occur during mode 4 (deployment) of the system life cycle are found as follows:

$$F_{N_4} = \lambda_D t_{D_4}$$

where

F_{N_4} = Expected failures during mode 4 under "no test" concept

λ_D = 29.235 failures/ 10^6 part-hours = Dormant failure rate

t_{D_4} = 1 to 5 years = Expected deployment time

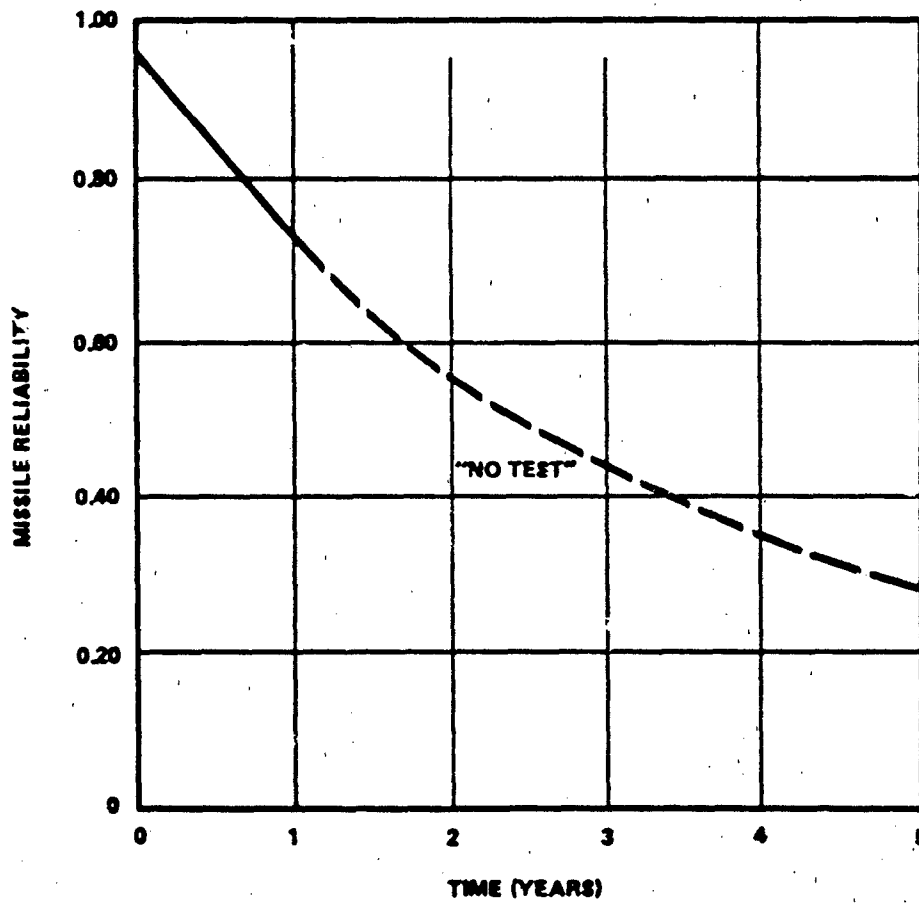
The model may be solved for the total expected failures for various durations, and, by utilizing the exponential equation, system reliability can be calculated.

Figure C-2 shows the system reliability degradation during the deployment mode under the "no test" concept. Note that the initial reliability is not 1.0, but 0.962, as calculated above, which is a result of the undetected failures through mode 3. Therefore, at the end of 5 years the system reliability would be approximately 0.26 which is not acceptable for most tactical missiles.

C.3.2 Periodic Test Concept

In order to maintain a higher reliability throughout deployment, a periodic test strategy may be chosen. Usually, trade studies are involved in selecting the optimum checkout interval. However, it shall

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BDM-A-61-616-TR

Figure C-2. Reliability Degradation with No Test Deployment Concept

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be assumed that the trade studies have already been performed, and a period test interval of one year selected.

An important consideration with the periodic test concept is the effects of power on/off cycling on the system reliability. If the system does not have adequate transient suppression circuitry, the power cycling may have a disastrous effect upon system reliability and availability. It shall be assumed that the system under consideration does have protection against transients. However, the power cycling will still cause some degradation to the system. This degradation will be assumed to occur only on the electronic portion of the system. Data from reference 18 will be used to quantify the effects of on-off cycling on the system reliability.

For calculating the estimated number of failures that occur between periodic tests, certain values relating to the test must be established. The interval between periodic tests will be one year. The total operating time during periodic test is assumed to be three hours, which also is sufficient time for the internal temperature rise to stabilize at the maximum operating value. The model for calculating the estimated failures is as follows:

$$F_p = \left[(N_C K_{C/D}) \lambda_{DE} + r_D \lambda_D + r_E \lambda_E \right] t_{D_4}$$

where

F_p = Expected failures during one periodic test interval

N_C = 0.00023 = Ratio of total power cycles to total periodic test interval time (cycles per hour)

$K_{C/D}$ = 270 = Ratio of cyclic failure rate to dormancy failure rate (estimated for an average mix of high reliability parts)

λ_{DE} = 14.876 failures/ 10^6 part-hours = Dormant failure rate of electronic parts

r_D = 0.99966 = Ratio of total dormant time to total periodic test interval time

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$\lambda_D = 29.235 \text{ failures}/10^6 \text{ part-hours} = \text{System dormant failure rate}$

$\lambda_E = 2067.520 \text{ failures}/10^6 \text{ part-hours} = \text{System energized failure rate}$

$r_E = 0.00034 = \text{Ratio of total operating time to total periodic test interval time}$

$t_{D_4} = 8,760 \text{ hours} = \text{Total periodic test interval time.}$

The failure rate values are taken from table C-1. The ratios, r_D and r_E , are based upon the assumption of a 1-year periodic test interval (8,760 hours) with a 3-hour operating time during test. A total of two power on-off cycles are assumed per test interval, from which N_C is obtained. The value of $K_{C/D}$ is assumed to have been, for this system, based upon such factors as high reliability parts, part mix, cyclic rate and duration, transient suppression capabilities, and energy level attained during cycling. Substituting these values into the model:

$$F_p = [(0.00023)(270)(14.876 \times 10^{-6}) + (0.99966)(29.235 \times 10^{-6}) + (0.00034)(2067.520 \times 10^{-6})] 8760$$

$$F_p = 0.2703 \text{ failures}$$

By combining the value calculated for F_p with that previously obtained for F_3 and applying the sum to the exponential equation, the system reliability just prior to the first periodic test is obtained:

$$R = e^{-(F_p + F_3)} = e^{-(0.3086)} = 0.734$$

Thus, by using the exponential equation, system reliability can be calculated at the time of test. Immediately after the periodic test, the reliability will be higher since detected failures will have been repaired. However, the reliability will not regain its former level at the previous periodic test because there are undetected failures remaining in the system.

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For comparative purposes it shall be assumed that the value of α_4 , the efficiency of the test in detecting failures, is 90 percent. The system reliability following first periodic test can be calculated in the following manner:

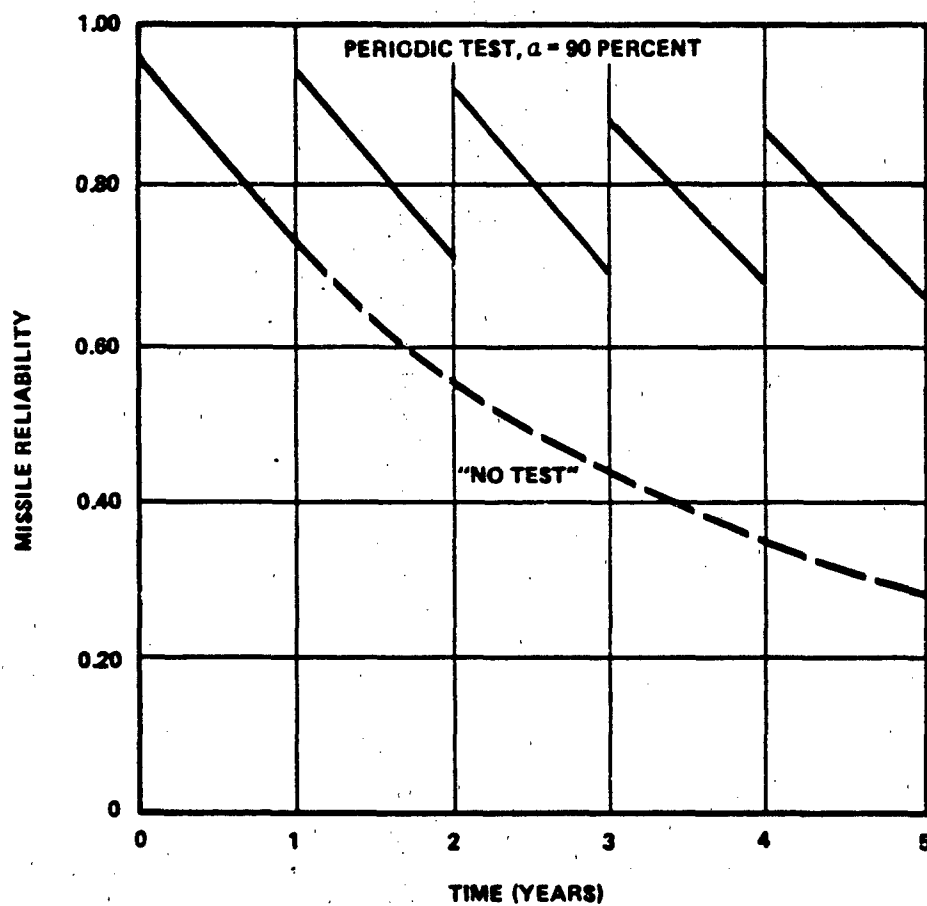
$$\begin{aligned} R &= e^{-[(1 - \alpha_4) (F_p) + F_3]} \\ R &= e^{-[.10(0.2703) + 0.0383]} \\ R &= e^{-0.0653} \\ R &= 0.937 \end{aligned}$$

Figure C-3 shows the resulting reliability degradation over a 5-year deployment period; the "no test" degradation for the same period of time is also designated by the dashed lines. Other than the dormant failure rate, the most significant contributors to achieving long term dormancy system reliability are the test efficiency and the frequency of periodic test.

C.4 SUMMARY

The life cycle model example presented in this annex demonstrates the utility of the methodology as a tool for projecting mature missile system operational reliability. As previously discussed, however, the level of detail required to adequately represent a specific missile system is dependent upon that missile's operation and maintenance concepts and its intended application environment.

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Figure C-3. Missile Reliability after 5 Years of Dormant Deployment Under "Wooden Round" and Periodic Test Concept

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ANNEX D

TIME TO FAILURE DISTRIBUTION AND STATISTICAL TEST DESIGN

D.1 INTRODUCTION.

It has been traditional to restrict the number of probability functions used in reliability work. It has been found that a relatively small number of functions satisfy most of the needs, and the statistical theory is not very well developed for many functions. One of the most often used functions is the exponential. This annex will provide a brief introduction to the exponential distribution, some basic reasons for its popular acceptance, a discussion of the notion of statistical test design, and some thoughts on validating the exponential model.

D.2 THE EXPONENTIAL DISTRIBUTION.

A typical life characteristic curve for a component or item can be defined by three failure components which predominate during the three periods of an item's life. These components can be described in terms of a hazard rate which can be simply stated as the conditional probability of failure. The failure components include:

- a) Early Failure--due to design and quality-rated manufacturing flaws and which have a decreasing hazard rate.
- b) Stress Related Failure--due to application stresses and which have a constant hazard rate.
- c) Wearout Failures--due to aging and/or deterioration and which have an increasing hazard rate.

The hazard rate varies with the principal periods of an item's life.

- a) The infant mortality period is characterized by a high but rapidly decreasing hazard rate that is composed of:
 - 1) a high quality failure component
 - 2) a constant stress related failure component
 - 3) a low wearout failure component.
- b) The useful life period is characterized by a constant hazard rate that is composed of:

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- 1) a low (and decreasing) quality failure component
- 2) a constant stress related failure component
- 3) a low (but increasing) wearout failure component.

Note: The combination of all three components results in a constant hazard rate because the decreasing quality failures and increasing wearout failures tend to offset each other, and because the stress related failures exhibit a relatively large amplitude.

- c) The wearout period is characterized by an increasing hazard rate that is composed of:
 - 1) a negligible quality failure component
 - 2) a constant stress related failure component
 - 3) an initially low but rapidly increasing wearout failure component.

The general approach to reliability for electronic systems is to minimize early failures by emphasizing factory test and inspection and preventing wearout failures by replacing short life parts. Consequently, the useful life period characterized by stress related failures is the most important period, and the one to which design action is primarily addressed.

During the useful life period the hazard rate is constant. A constant hazard (or failure) rate is described by the exponential failure distribution. Thus, the exponential failure model reflects the fact that the item must represent a mature design whose failure rate, in general, is primarily comprised of stress related failures. This means that early failures have been minimized, and wearout is not noticeable or is beyond the period of concern. The magnitude of this failure rate is directly related to the stress/strength ratio of the item.

The exponential model can be derived from the basic notions of probability. When a fixed number, N_0 , of components are repeatedly tested, there will be, after a time, t , N_s components which survive the test and N_f components which fail. The reliability or probability of survival is at any time t during the test:

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$$R(t) = \frac{N_s}{N_0} = \frac{N_s}{(N_s + N_f)}$$

Since $N_s = N_0 - N_f$, reliability can be written:

$$R(t) = \frac{N_0 - N_f}{N_0} = 1 - \frac{N_f}{N_0} = 1 - F(t)$$

and

$$\frac{dR}{dt} = -\frac{1}{N_0} \frac{dN_f}{dt} = -f(t)_i$$

where $f(t)_i$ = the failure density function, i.e., the probability that a failure will occur in the next time increment dt .

The hazard rate $z(t)$ is defined as the ratio of the fractional failure rate to the fractional surviving quantity, that is, number of the original population still operating at time t , or simply the conditional probability of failure.

$$\begin{aligned} z(t) &= \frac{f(t)}{R(t)} = \frac{f(t)}{1-F(t)} \\ &= \frac{f(t)}{1 - \int_0^t f(t)dt} \end{aligned}$$

For the exponential distribution,

$$f(t) = \lambda e^{-\lambda t}$$

$$z(t) = \lambda$$

In general, it can be assumed that the hazard rate of electronic elements and systems remains constant over practical intervals of time, and that $z(t)_i = \lambda_i$. Hence, λ_i , a constant, represents the expected number of random failures per unit of operating time of the i^{th} element, i.e., the failure rate. Thus, when a constant failure rate can be assumed:

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$$z(t)_i = \lambda_i = \frac{f(t)_i}{R(t)_i} = \frac{-\frac{dR(t)_i}{dt}}{R(t)_i}$$

Solving this differential equation for $R(t)_i$ gives the exponential distribution function commonly used in reliability prediction:

$$R(t)_i = e^{-\lambda_i t}$$

Also, the mean time to failure can be determined by:

$$MTBF = \int_0^{\infty} R(t) dt,$$

so that, when a constant failure rate λ_i can be assumed:

$$MTBF_i = \int_0^{\infty} e^{-\lambda_i t} dt = \frac{1}{\lambda_i}.$$

The above expressions for $R(t)_i$ and $MTBF_i$ are the basic mathematical relationships used in reliability prediction. It must be emphasized, however, that these expressions were derived based on the fundamental assumption that the failure rate of the item under consideration is a constant.

D.3 REASONS FOR ACCEPTING THE EXPONENTIAL DISTRIBUTION.

The emphasis on the exponential distribution in reliability work makes it worthwhile to discuss the use of this function as a failure-probability model. The mechanism underlying the exponential reliability function is that the hazard rate (or the conditional probability of failure in an interval given survival at the beginning of the interval) is independent of the accumulated life.

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The use of this type of "failure law" for complex systems is judged applicable because of the many forces that can act upon the item and produce failure. As stated previously, the stress/strength relationship and varying environmental conditions result in essentially random failures.

Another factor for assuming the exponential distribution in long-life complex systems is the so-called "approach to a stable state," wherein the system hazard rate is effectively constant regardless of the failure pattern of individual parts. This state results from the mixing of part ages when failed elements in the system are replaced or repaired. Over a period of time, the system hazard rate oscillates, but this cyclic movement diminishes in time and approaches a stable state with a constant hazard rate.

A third argument for assuming the exponential distribution is that the exponential can be used as an approximation of some other function over a particular interval of time for which the true hazard rate is essentially constant.

D.4 STATISTICAL TEST DESIGN.

The objective of statistical testing is to make a decision with a specified level of confidence concerning the risks to both the user and the developer in rejecting the test parameter.

The underlying theory in developing test methodologies, and in particular dormant reliability testing, is sound; however, rarely is a dormant reliability test structured during IOT&E/FOT&E with fully committed assets. In the dormant environment, high lifetimes are expected, and to develop a test to obtain a high confidence in the outcome would involve long test periods and/or large sample sizes. Also, cost restrictions dictate that limited assets can be allocated for dormant testing purposes.

In testing for dormant reliability, it is frequently necessary to decide if a system meets certain desired or specified goals. This is where hypothesis testing is used.

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D.4.1 Hypothesis Testing.

Hypothesis testing requires stating a null hypothesis, H_0 , concerning the mean time to failure of the items under test, where this mean time to failure, θ , is the mean of the exponential distribution. An alternative hypothesis, H_1 , which is less than or greater than H_0 , is implied or specified in these test methodologies.

For example, a null hypothesis might be that the mean time to failure is greater than or equal to 20,000 hours (θ_0). The alternative hypothesis might be that the mean time to failure is less than 5,000 hours (θ_1). The 20,000 hours might be a system specification value (desired value) and the 5,000 hours would represent the minimum acceptable value, i.e., the threshold.

A statement of the above hypothesis in general form is:

$$H_0: \theta \geq 20,000 \text{ hours}$$

$$H_1: \theta < 5,000 \text{ hours}$$

Two types of errors present themselves during hypothesis testing:

- a) Type I - rejecting the null hypothesis, H_0 , when it is true. The probability of this type of error is represented by α , and is called the developer's risk, or level of significance.
- b) Type II - accepting the null hypothesis when in fact the alternative hypothesis is true. The probability of this type of error is represented by β , and is called the user's risk.

Tradeoffs between α and β can be made, but the required sample size becomes larger for a higher degree of certainty of making the correct decision. The α and β should be specified before any testing is done.

D.4.2 Chi-Square Distribution.

Kapur and Lamberson (1977) reference 12, state that if t is exponentially distributed, then the statistic $\frac{2t}{\theta_0}$ is distributed as $\chi^2(2r)$, with

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t being the total test time and r the number of failures. The degrees of freedom for this chi-square statistic are $2r$.

A test of the hypothesis discussed above involves the use of the above chi-square statistic. H_0 is rejected when that statistic, $\frac{2t}{\theta_0}$, is too small. The statistic is too small when its value falls below the chi-square critical value.

If H_0 is true, a $100(1-\alpha)$ percent confidence interval for θ is given by

$$P \left[\frac{2t}{\chi^2_{(1-\alpha, 2r)}} \leq \theta \right] = 1 - \alpha$$

D.4.3 Sample Size Determination.

Two commonly used test methods which can be employed in dormant reliability testing are fixed-length tests and tests which are truncated after a predetermined number of failures have occurred. During testing, failed items may or may not be replaced after being repaired. Each situation will be discussed.

D.4.3.1 Fixed-Time Test With Replacement.

The test situation requires that some number, n , of the systems be tested for a specified period of time, t . Once θ_0 , θ_1 , α , and β are specified, the acceptable number of failures, r , is determined by choosing the smallest r for which

$$\frac{\chi^2_{(1-\alpha, 2r)}}{\chi^2_{(\beta, 2r)}} \geq \frac{\theta_1}{\theta_0}$$

During testing, if the number of failures observed is greater than r , the null hypothesis (i.e., $\theta \geq 20,000$ hours) can be rejected with a $100(1-\alpha)$ percent confidence that a Type I error has not been committed. Once r is determined, the sample size is determined by the formula

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$$n = \frac{\theta_0^2 x^2 (1-\alpha, 2r)}{2t}$$

For example, let the null and alternative hypotheses be

$$H_0: \theta \geq 20,000 \text{ hours}$$

$$H_1: \theta < 5,000 \text{ hours}$$

and let $\alpha = .10$ and $\beta = .05$. Then $r = 5$, and if the test time is $t = 5,000$, the required sample size is

$$n = \frac{20,000 (4.865)}{2 (5,000)}$$

$$n = 9.73$$

and $n = 10$ is selected to provide an integer value for the sample size.

D.4.3.2 Fixed-Time Test Without Replacement.

The number of acceptable failures, r , is determined as above, but the sample size, n , is determined by

$$n = \left[r / (1 - e^{-t/c}) \right],$$

where

$$c = \theta_0^2 x^2 (1-\alpha, 2r) / 2r$$

$$c = 20,000 (6.57) / 10$$

$$c = 13,140.$$

Then

$$n = [5 / (1 - e^{-5000/13140})]$$

$$n = 15.79$$

and $n = 16$ is selected.

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D.4.3.3 Tests Truncated After a Fixed Number of Failures.

If n items are randomly selected for testing, and testing is terminated when the r -th failure occurs, there is no established rule for determining what the sample size, n , should be. The number of failures, r , is determined as above. By looking at the sample size formula in paragraph D.4.3.1, it can be seen that the effect of increasing n is to shorten the necessary test time. If available test time is limited and the test items are not expensive, a test in which the first r failures ($r \leq n$) out of n items tested might be preferred. If test items are expensive and there is ample test time available, a test based on r failures ($r = n$) out of n items tested might be preferred.

Whether with or without replacement, the procedure for estimating the mean life, θ , in tests truncated at the r -th failure remains the same. The formula for computing the estimate of the mean life, $\hat{\theta}$, of the sample changes slightly depending on whether the test is with or without replacement of failed items. See reference 30 for further information.

D.4.3.4 Sequential Life Tests.

Improvements on the procedures of paragraphs D.4.3.1 - D.4.3.3 can be made by the use of a sequential procedure. At any point in time during testing a decision may be made to accept, reject, or continue testing. See reference 30 for the details of this procedure.

D.4.4 Determining Statistical Confidence With Limited Assets.

If the assets provided are less than the number determined necessary in paragraph D.4.3.1, either the $100(1-\alpha)$ percent confidence level will change, or the number of acceptable failures (including the value of β) will change.

Determination of the $100(1-\alpha)$ percent confidence level and β value in both cases will be explained in the following paragraphs.

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D.4.4.1 Change In User Risk and Allowable Failures With Limited Assets.

Given: Systems Required: $n = 10$

Systems Provided: $n = 5$

$\alpha = .10$

$\theta_0 = 20,000$ hours

$\theta_1 = 5,000$ hours

$t = 5,000$ hours

$$n = \frac{\theta_0 x^2 (1-\alpha, 2r)}{2t}$$

$$x^2 (1-\alpha, 2r) = \frac{2nt}{\theta_0}$$

$$x^2 (.90, 2r) = \frac{2 \times 5 \times 5000}{20,000}$$

$$= 2.5$$

Determine the r' value (new number of acceptable failures) associated with a chi-square critical value of 2.5 and $1-\alpha = .90$. A conservative value of $r' = 3$ is selected.

The user's risk, β , must increase to .20, since

$$\frac{x^2 (.90, 6)}{x^2 (\beta, 6)} \text{ must still } \geq .25.$$

D.4.4.2 Change In User and Developer Risk With Limited Assets.

Given: Systems Required: $n = 10$

Systems Provided: $n = 5$

Acceptable Failures: $r = 5$

$\theta_0 = 20,000$ hours

$\theta_1 = 5,000$ hours

$t = 5,000$ hours

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$$n = \frac{\theta_0^2 x^2 (1-\alpha, 2r)}{2t}$$

$$x^2_{(1-\alpha, 2r)} = \frac{2nt}{\theta_0^2}$$

$$x^2_{(1-\alpha, 10)} = \frac{2(5)(5,000)}{20,000} = 2.5$$

Determine the new α level from a chi-square table in the degrees of freedom row labeled 10. This gives $1-\alpha \approx .99$, which implies the new $\alpha = .01$.

Once the new α is determined, the new β may also be found since

$$\frac{x^2_{(.99, 10)}}{x^2_{(\beta, 10)}} \text{ must still } \geq .25$$

β must be approximately .42.

D.4.5 Validating the Exponential Failure Model.

The exponential failure model is the most commonly used distribution in life testing situations. However, frequently it is used because it is the easiest model to apply and not necessarily the correct model to use.

Several tests are available to validate the hypothesis that the time to failure data is representative of an exponential distribution. Kapur and Lamberson (reference 12) state that one of the most powerful tests available to detect "either an increasing or decreasing failure rate is Bartlett's test." The test statistic is given by:

$$B_r = \frac{2r \left[\ln\left(\frac{t_r}{r}\right) - \frac{1}{r} \left(\sum_{i=1}^r \ln x_i \right) \right]}{1 + (r+1)/6r}$$

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where X_i is a random variable representing time to failure, r is the number of failures, and $t_r = \sum_{i=1}^r X_i$.

"Under the hypothesis of an exponential distribution, the statistic B_r is chi-square distributed with $r-1$ degrees of freedom, and a two-tailed chi-square test is in order." Reject the hypothesis that mean time to failure follows an exponential distribution if B_r does not fall in the interval

$$\left[\chi^2_{(1 - \frac{\alpha}{2}, r-1)}, \chi^2_{(\frac{\alpha}{2}, r-1)} \right].$$

If the hypothesis is rejected, then another distribution model will have to be identified to represent time to failure.

Other candidate distribution models which have frequently been used in life testing include the normal, log normal, Weibull, and gamma. The Weibull distribution is probably the most widely used distribution for life testing applications after the exponential distribution. Generally, determination of the proper distribution model is a difficult task unless considerable test data are available. For example, distribution models such as the Weibull, log normal, and gamma will generally fit well in the middle of the range of the random variable but differ in the tails of the distribution. Such a condition is not favorable since the focus in reliability work is on high reliability, and the tails of the distribution tend to be most important. There are several statistical goodness-of-fit tests which can be used in the distribution selection process, but their utility is often limited because of the paucity of test data. Experience with similar systems and brute force graphical plotting techniques (e.g., histograms, probability paper, etc.) may provide the best means for selecting a failure distribution model.

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D.5 SUMMARY.

The exponential distribution is the most commonly used distribution in life testing applications. Its general applicability in complex systems is based upon the accepted assumption that the system time to failure distribution will approach the exponential even though the individual components may have different failure distributions. Statistical hypothesis testing based upon well-defined evaluation criteria provides the foundation for determining the appropriate sample size for failure testing. While the exponential distribution is widely accepted and applicable across a broad spectrum of situations, its validity should be established against the actual test data. If the exponential distribution cannot be accepted, then a search for an acceptable failure distribution model must be initiated.

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ANNEX E ELECTRONIC EQUIPMENT SCREENING METHODS

E.1 INTRODUCTION.

Part screening was introduced in section IV as a form of accelerated testing applied during the infant mortality phase of the equipment's life. Screening tests are generally used to compress the early failure period and reduce the failure rate to an acceptable level as quickly as possible. Table E-1 has been extracted from the Reliability Design Handbook (reference 34) to provide a convenient reference source of potential screening methods. The use of screening methods as part of acceptance testing appears feasible but deserves further study.

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Table E-1. Comparison of Screening Methods

Screen	Defects	Effectiveness	Cost	Comments
Interval visual inspection	Lead dress Metallization Oxide Particle Die bond Wire bond Contamination Corrosion Substrate		Inexpensive to moderate	This is a mandatory screen for high-reliability devices. Cost will depend upon the depth of the visual inspection.
Infrared	Design (thermal)	Very good	Expensive	For use in design evaluation only.
X-Ray	Die bond Lead dress (gold) Particle Manufacturing (gross errors) Seal Package Contamination	Excellent Good Good Good Good Good Good	Moderate	The advantage of this screen is that the die-to-header bond can be examined and some inspection can be performed after encapsulation. However, some materials are transparent to X-rays (i.e., Al and Si) and the cost may be as high as six times that of visual inspection, depending upon the complexity of the test system.
High temperature storage	Electrical (stability) Metallization Bulk silicon Corrosion	Good	Very inexpensive	This is a highly desirable screen.
Temperature cycling	Package Seal Die bond Wire bond Cracked substrate Thermal mismatch	Good	Very inexpensive	This screen may be one of the most effective for aluminum lead systems.
Thermal shock	Package Seal Die bond Wire bond Cracked substrate Thermal mismatch	Good	Inexpensive	This screen is similar to temperature cycling but induces higher stress levels. As a screen it is probably no better than temperature cycling.
Constant acceleration	Lead dress Die bond Wire bond Cracked substrate	Good	Moderate	At 20,000-G stress levels, the effectiveness of this screen for aluminum is questionable.
Shock (unmonitored)	Lead dress	Poor	Moderate	The drop-shock test is considered inferior to constant acceleration. However, the pneumatic shock test may be more effective. Shock tests may be destructive.
Shock (monitored)	Particles Intermittent short Intermittent open	Poor Fair Fair	Expensive	Visual or X-ray inspection is preferred for particle detection.
Vibration fatigue	Lead dress Package Die bond Wire bond Cracked substrate	Poor	Expensive	This test may be destructive. Except for work hardening, it is without merit.
Vibration variable frequency (unmonitored)	Package Die bond Wire bond Substrate	Fair	Expensive	
Vibration variable frequency (monitored)	Particles Lead dress Intermittent open	Fair Good Good	Very expensive	The effectiveness of this screen for detecting particles is part-dependent.

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Table E-1. Comparison of Screening Methods (Concluded)

Screen	Defects	Effectiveness	Cost	Comments
Random vibration (unmonitored)	Package Die bond Wire bond Substrate	Good	Expensive	This is a better screen than VVF (unmonitored) especially for space-launch equipment, but it is more expensive.
Random vibration (monitored)	Particles Lead dress Intermittent open	Fair Good Good	Very expensive	This is one of the most expensive screens; when combined with only fair effectiveness for particle detection, it is not recommended except in very special situations.
Helium leak test	Package Seals	Good	Moderate	This screen is effective for detecting leaks in the range of 10^{-8} to 10^{-10} Atm cc/sec.
Radiflo leak test	Package Seals	Good	Moderate	This screen is effective for leaks in the range of 10^{-8} to 10^{-12} Atm cc/sec.
Nitrogen bomb test	Package Seals	Good	Inexpensive	This test is effective for detecting leaks between the gross-and-fine-leak-detection ranges.
Gross-leak test	Package Seals	Good	Inexpensive	Effectiveness is volume-dependent. Detects leaks greater than 10 Atm cc/sec.
High-voltage test	Oxide	Good	Inexpensive	Effectiveness is fabrication dependent.
Isolation resistance	Lead dress Metallization Contamination	Fair	Inexpensive	
Intermittent operation life	Metallization Bulk silicon Oxide Inversion/ channeling Design Parameter drift Contamination	Good	Expensive	Probably no better than ac operating life.
Ac operating life	Metallization Bulk silicon Oxide Inversion/ channeling Design Parameter Contamination	Very good	Expensive	
Dc operating life	Essentially the same as intermittent life.	Good	Expensive	No mechanisms are activated that could not be better activated by ac life tests.
High-temperature ac operating life	Same as ac operating life	Excellent	Very expensive	Temperature acts to accelerate failure mechanisms. This is probably the most expensive screen and one of the most effective.
High-temperature reverse bias	Inversion/ channeling	Poor	Expensive	

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ANNEX F

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